Perchlorate at the Santa Susana Field Laboratory

Presentation to the

Perchlorate Public Advisory Group
Los Angeles Regional Water Quality Control Board

Friday, May 23, 2003

Presented by:

Richard Andrachek, PE & Dr. Ross Wagner, RG, of MWH

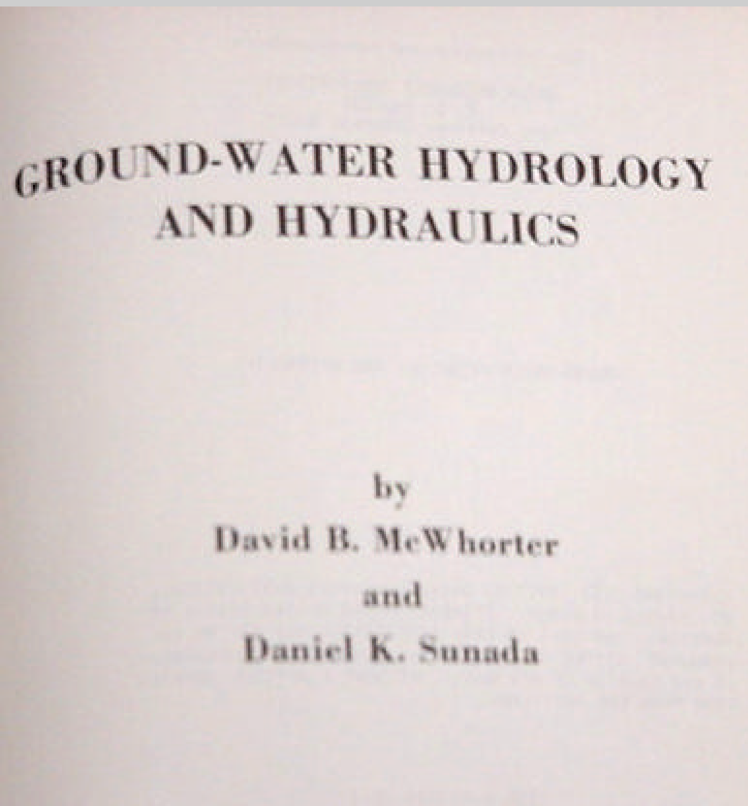
&

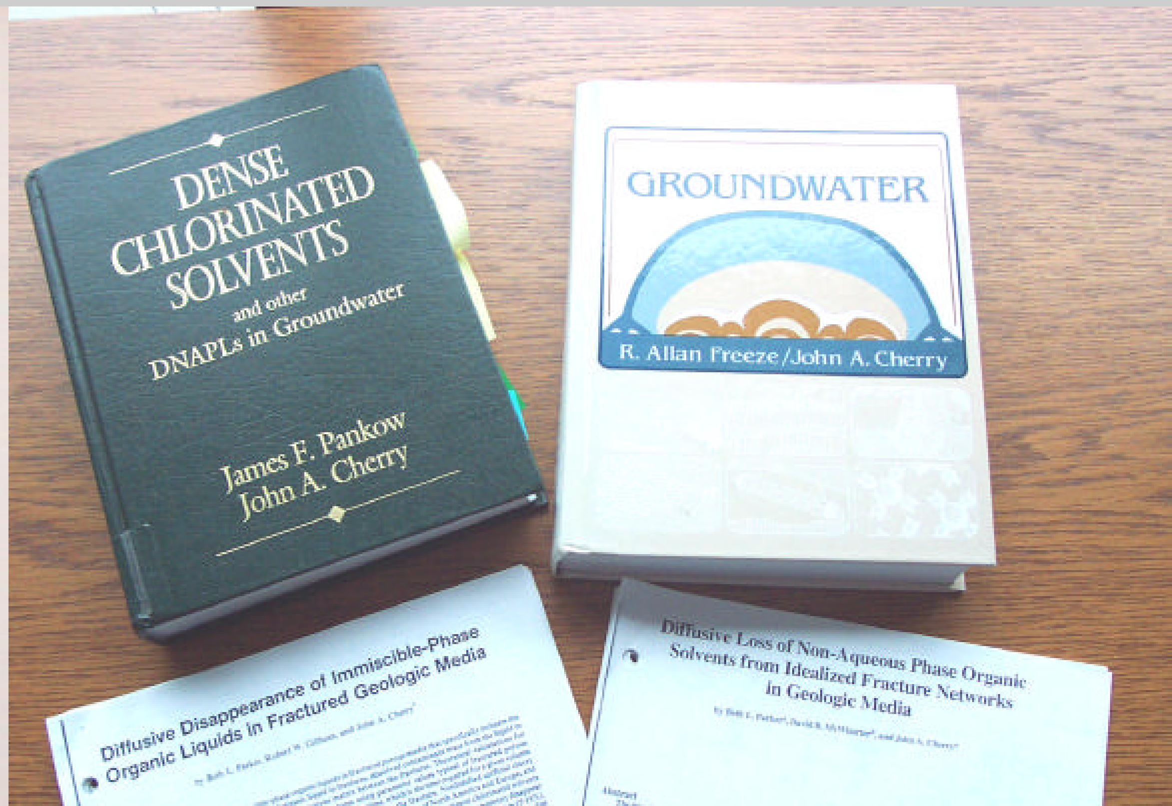
Groundwater Advisory Panel

Drs. John Cherry, Beth Parker and David McWhorter

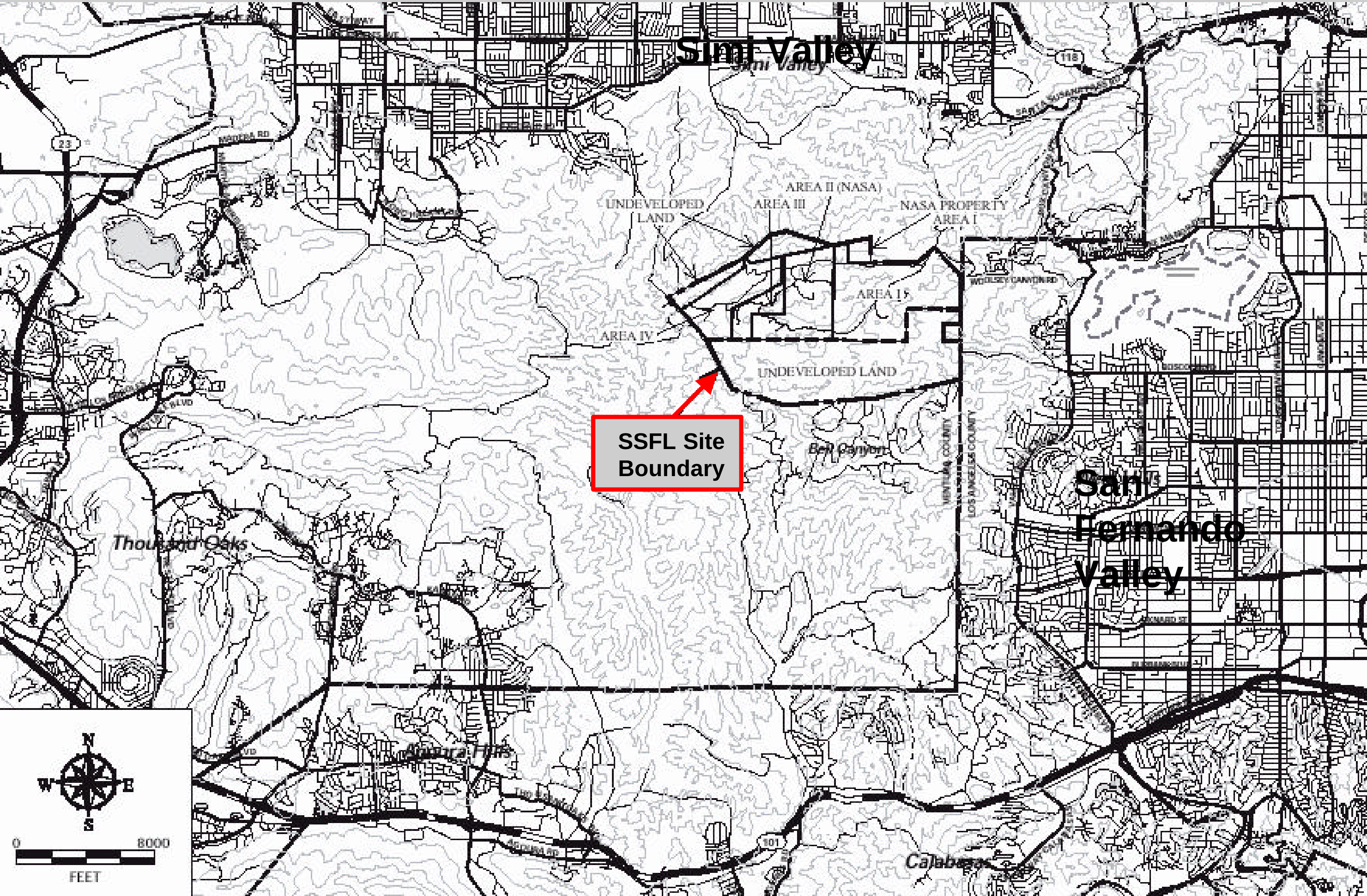
Introduction for Groundwater Advisory Panel

- Wrote the Books in 1977, 1979, 1996
- Wrote the Papers on Molecular Diffusion into Porous Fractured Rocks in 1994, 1996





SSFL is Located Atop the Simi Hills with Residential Communities Located in Valleys ~ 3 miles north and 1 mile south and east of the SSFL



Utilize Question and Answer Format to Review Material

<u>Major Topics of Discussion To Include:</u>

- Was perchlorate used at the SSFL and if so, where and for what?
- Have samples of soil, sediment, groundwater, surface water and springs/seeps been collected and analyzed for perchlorate? If so, where? What do the results show?
- Has perchlorate at SSFL been transported off-site by surface water? Atmospheric deposition? Groundwater?
- What can be concluded about perchlorate at the SSFL from the data that have been collected?
- Is further work necessary and if so, when will it be completed?

Was perchlorate used at the SSFL? If so, for what?

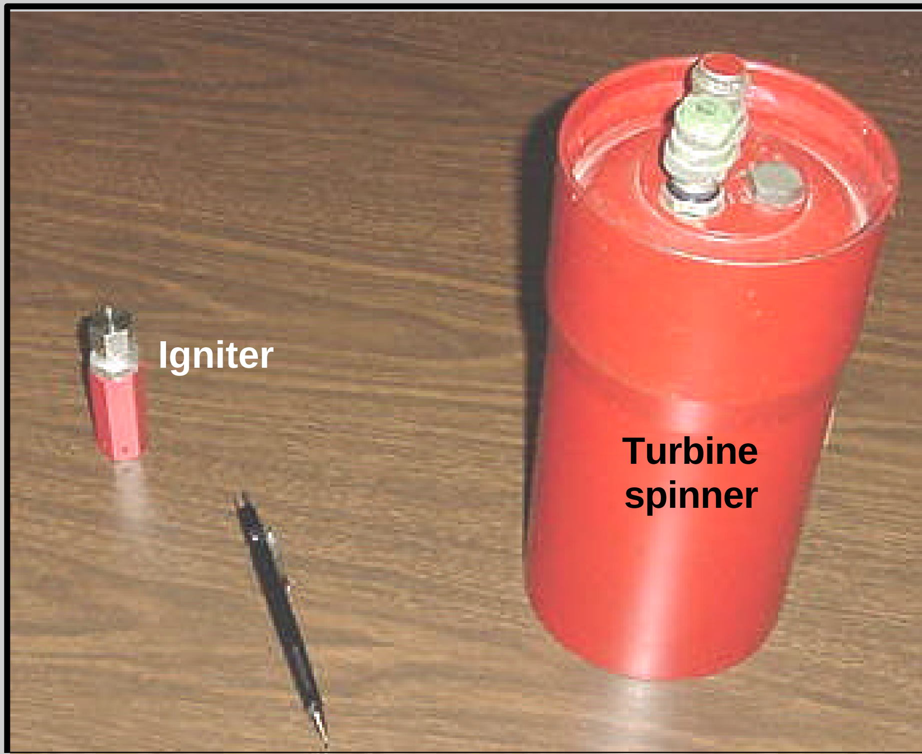
The three primary uses of perchlorate at the SSFL have been:

1. Turbine spinner and igniter development, testing and use during the ‘50s and ‘60s.

- **Igniters continued to be used at active test stands**
- **Produced and assembled offsite.**

2. Flare research, development, and production during the ‘60s

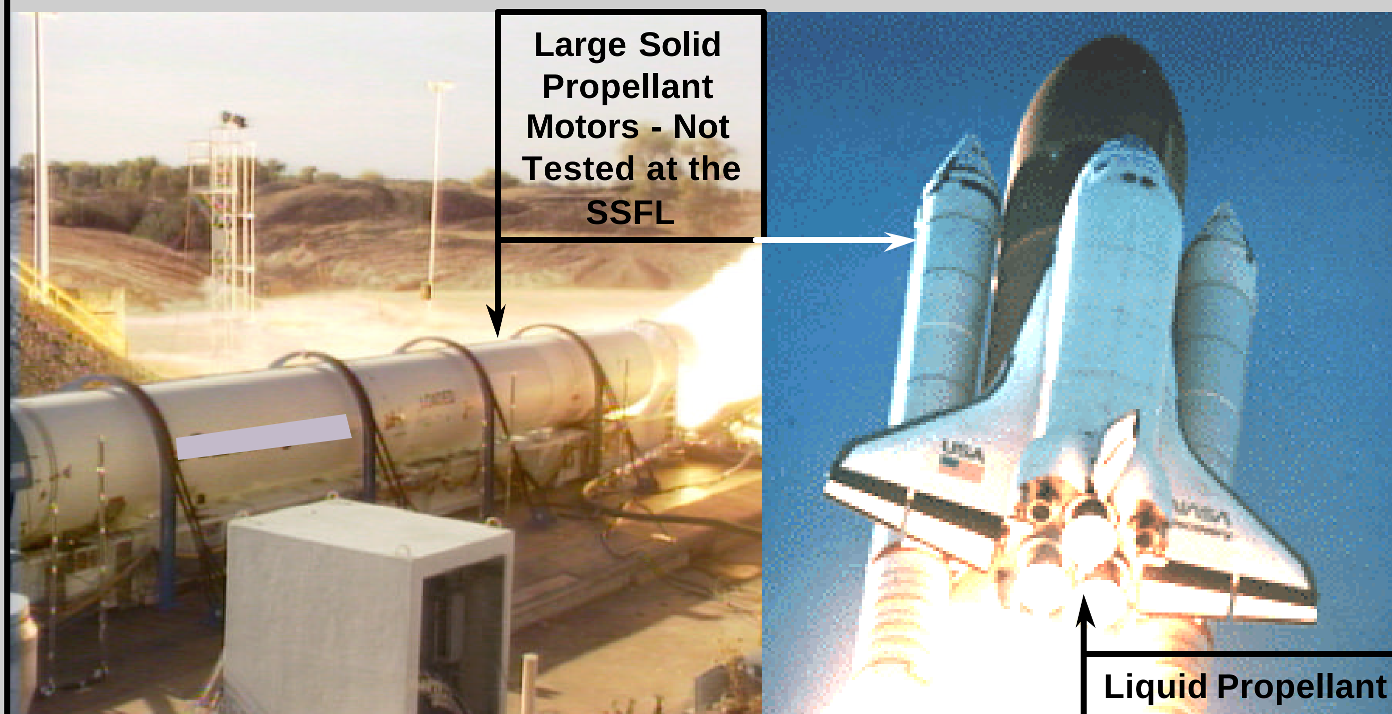
3. Small solid-rocket propellant research, development, and testing from the ‘70’s to ‘94



Many Rocket Engines were Tested at the SSFL, Wasn't a Lot of Perchlorate Used?

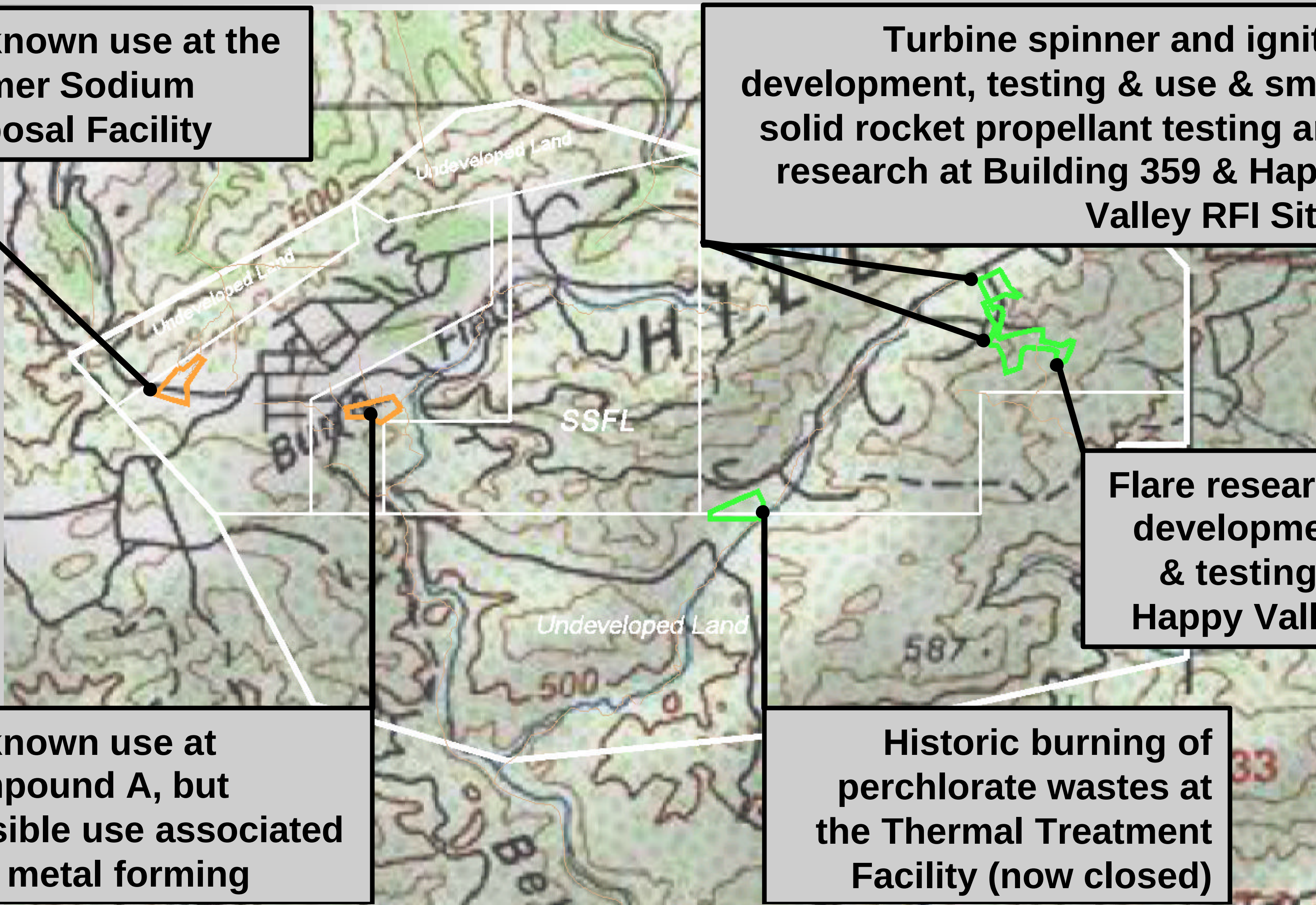
No, Because Liquid-Propelled Engines Were Primarily Tested and They Don't Use Perchlorate as the Oxidizer

Solid Propellant Motors for Lifting Spacecraft into Orbit are Large and were <u>NOT</u> Tested at the SSFL



Was perchlorate used at the SSFL? If so, where?

Perchlorate was primarily used at the Building 359 and Happy Valley Sites



No known use at the Former Sodium Disposal Facility

Turbine spinner and igniter development, testing & use & small solid rocket propellant testing and research at Building 359 & Happy Valley RFI Sites

Flare research development & testing at Happy Valley

No known use at Compound A, but possible use associated with metal forming

Historic burning of perchlorate wastes at the Thermal Treatment Facility (now closed)

Have samples of soil, sediment, groundwater, surface water and springs/seeps been collected and analyzed for perchlorate?

More than 1,600 samples were collected between 1997 and Jan of 2003

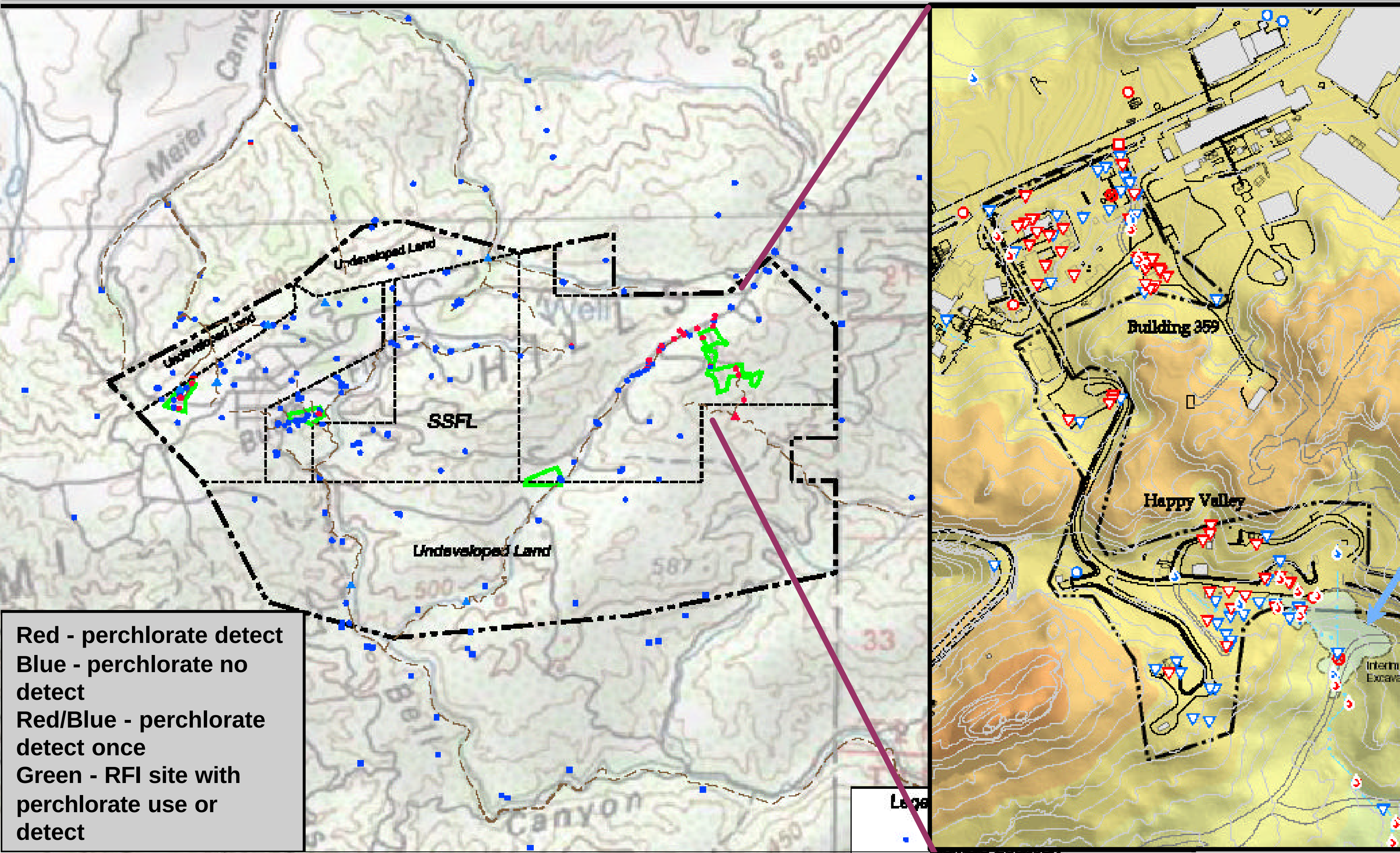
- **Soil: 461**
- **Surface Water: 281**
- **Spring/Seep: 25**
- **Groundwater: 855**
- **Treated GW: 35**

Approximately 300 more have been collected since Feb 2003

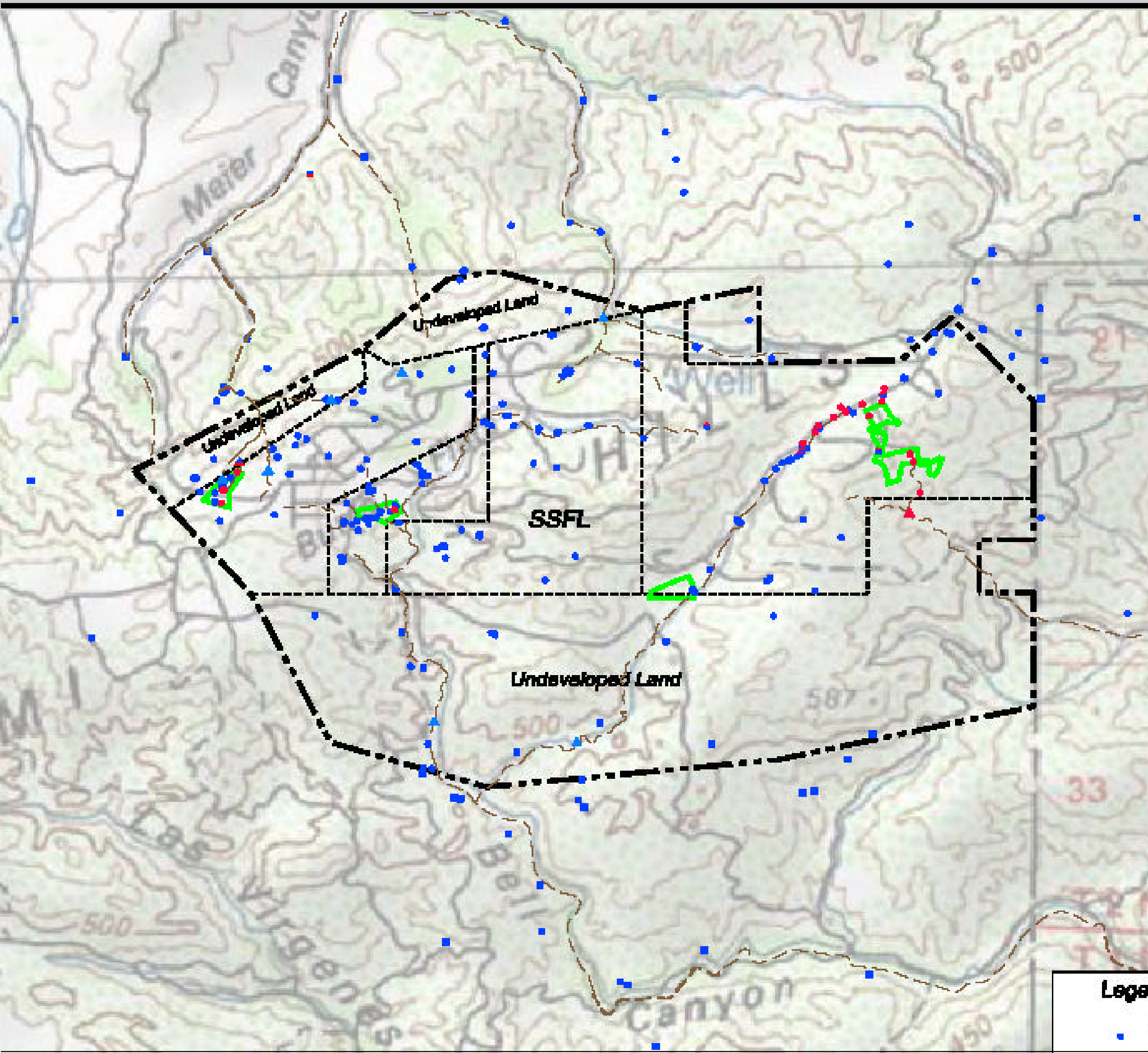
Table ID and Description	Location of Sampling Program	Number of Samples	Number of Detects	Maximum Detected	Minimum Detected	Units
4-1A. RFI Soil	Onsite	178	41	71.29	0.02	mg/kg
4-1B. RFI Soil Leachate	Onsite	69	44	10	0.005	mg/L
4-1C. RFI Sumps/Contained Units	Onsite	3	2	0.44	0.04	mg/kg
4-1D. Happy Valley B372 Demolition	Onsite	10	10	130.669	0.0225	mg/kg
4-1E. DTSC Split RFI Soil	Onsite	3	0	--	--	mg/kg
4-1F. DTSC Split RFI Leachate	Onsite	6	0	--	--	mg/L
4-1G. Happy Valley IM Soil	Onsite	23	9	0.16	0.02	mg/kg
4-1H. FSDF IM Soil	Onsite	114	4	1.3	0.44	mg/kg
4-1I. DTSC Split FSDF IM Soil	Onsite	7	0	--	--	mg/kg
4-1J. Bell Canyon Soil Samples	Offsite	24	0	--	--	mg/kg
4-1K. DTSC North Drainage Soil	Offsite	5	0	--	--	mg/kg
4-1L. DTSC North Drainage Leachate	Offsite	19	1	0.0046	0.0046	mg/L
Total Soil		**461**	**111**			
4-1M. RFI Surface Water	Onsite	29	15	0.058	0.0042	mg/L
4-1N. NPDES Surface Water	Onsite	252	18	0.0351	0.0042	mg/L
Total Surface Water		**281**	**33**			
4-1O. RFI Spring and Seep	Offsite	17	0	--	--	mg/L
4-1P. DTSC Split Spring and Seep	Offsite	8	0	--	--	mg/L
Total Spring and Seep		**25**	**0**			
4-1Q. Near-Surface Groundwater Wells	Onsite	170	36	0.048	0.0011	mg/L
4-1R. DTSC Split Near-Surface Groundwater	Onsite	4	4	0.025	0.004	mg/L
4-1S. Onsite Chatsworth Formation Wells	Onsite	409	76	0.750	0.0018	mg/L
4-1T. Offsite Chatsworth Formation Wells	Offsite	186	2	0.005	0.004	mg/L
4-1U. Chatsworth Formation - FLUTe	Onsite	76	34	1.600	0.0044	mg/L
4-1V. DTSC Split Chatsworth Formation - FLU	Onsite	10	1	0.00479	0.00479	mg/L
4-1W. Groundwater Treatment System	Onsite	35	7	0.0078	0.0052	mg/L
Total Groundwater		**890**	**160**			
TOTAL SAMPLES		**1657**	**304**			
Total Onsite Samples		**1398**	**301**			
Total Offsite Samples		**259**	**3**			

Where were perchlorate samples collected?

On-site & off-site in all directions



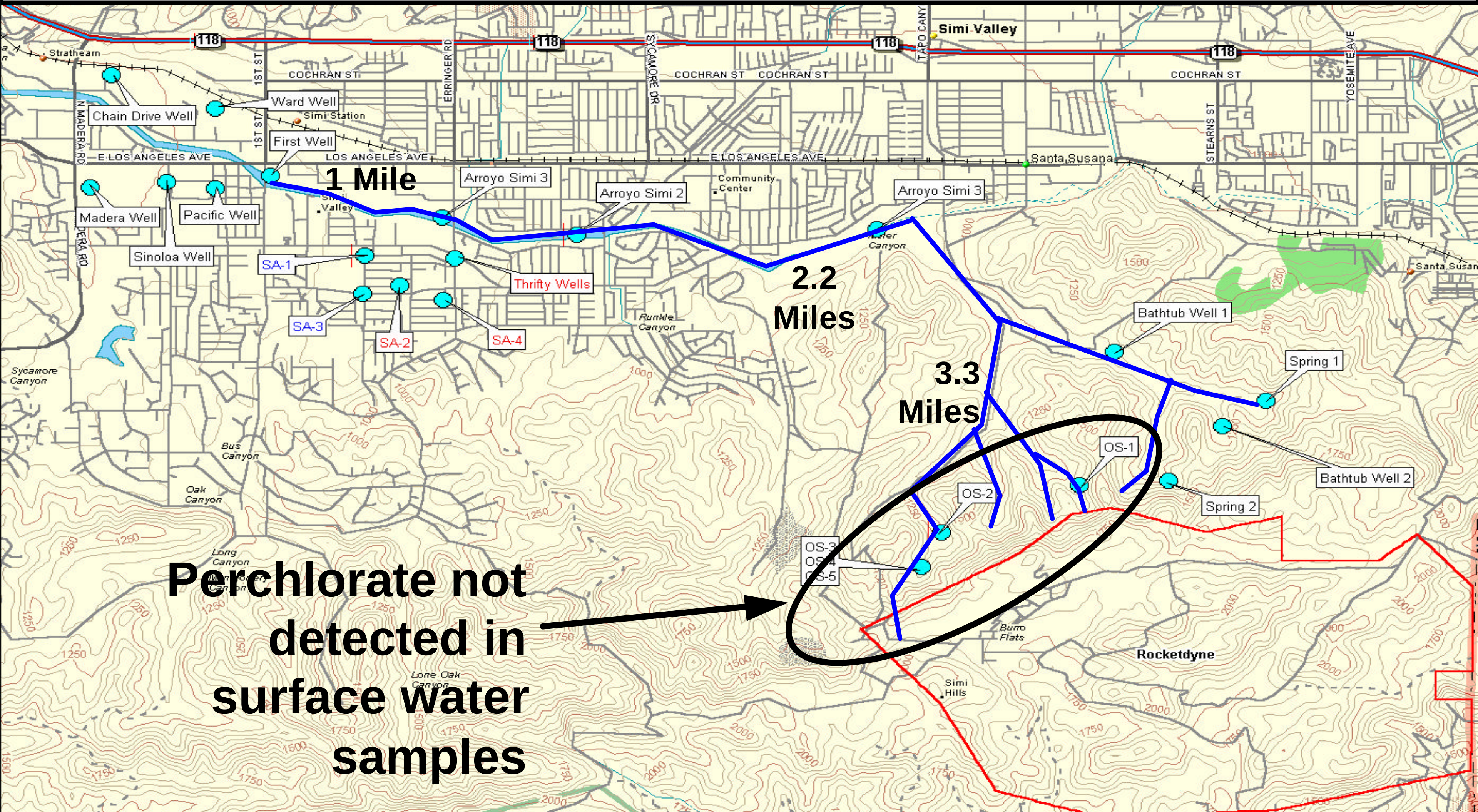
What do perchlorate sampling results show?



1. A source in soil is coincident with where it is detected in groundwater.
2. The vertical and lateral extent of perchlorate in groundwater is contained on-site.
3. There are no repeatable detections of perchlorate off-site.
4. Consistent low-level detection in surface water in Happy Valley Drainage.

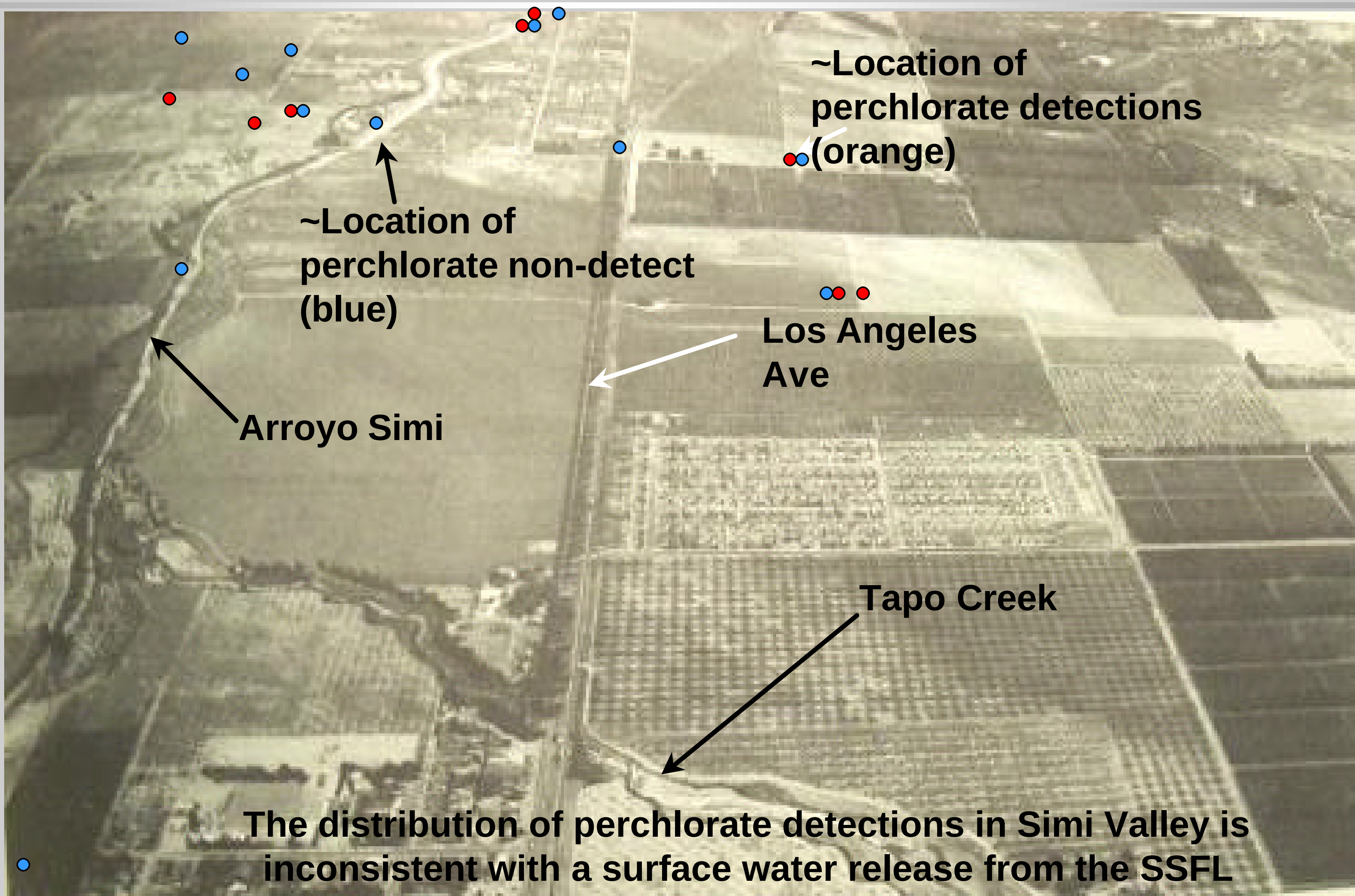
Has perchlorate been transported off of the SSFL by surface water into Simi Valley?

Transport by surface water runoff to the Simi Valley

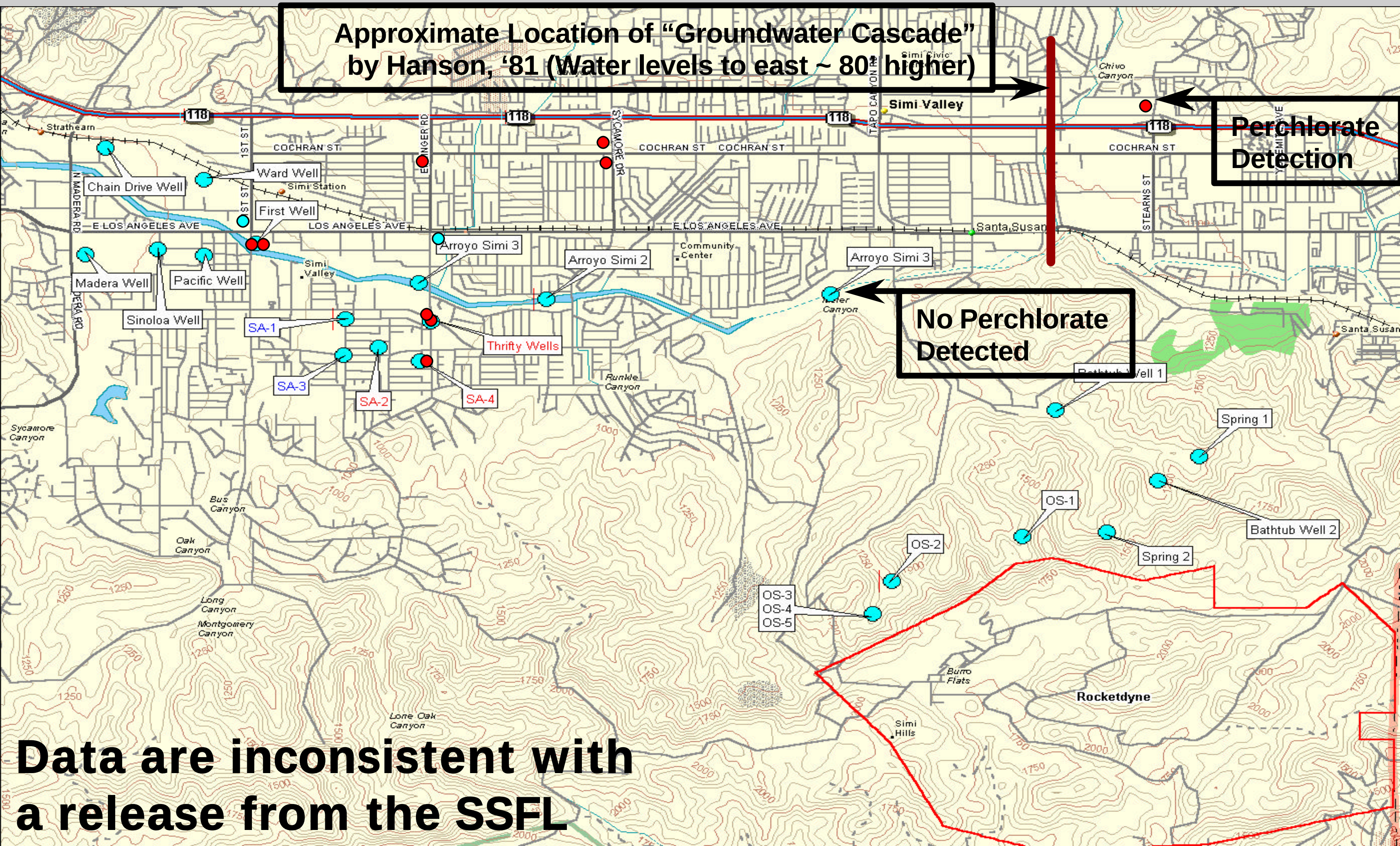


Perchlorate not detected in surface water samples

Has perchlorate been transported off of the SSFL to Simi Valley by surface water?



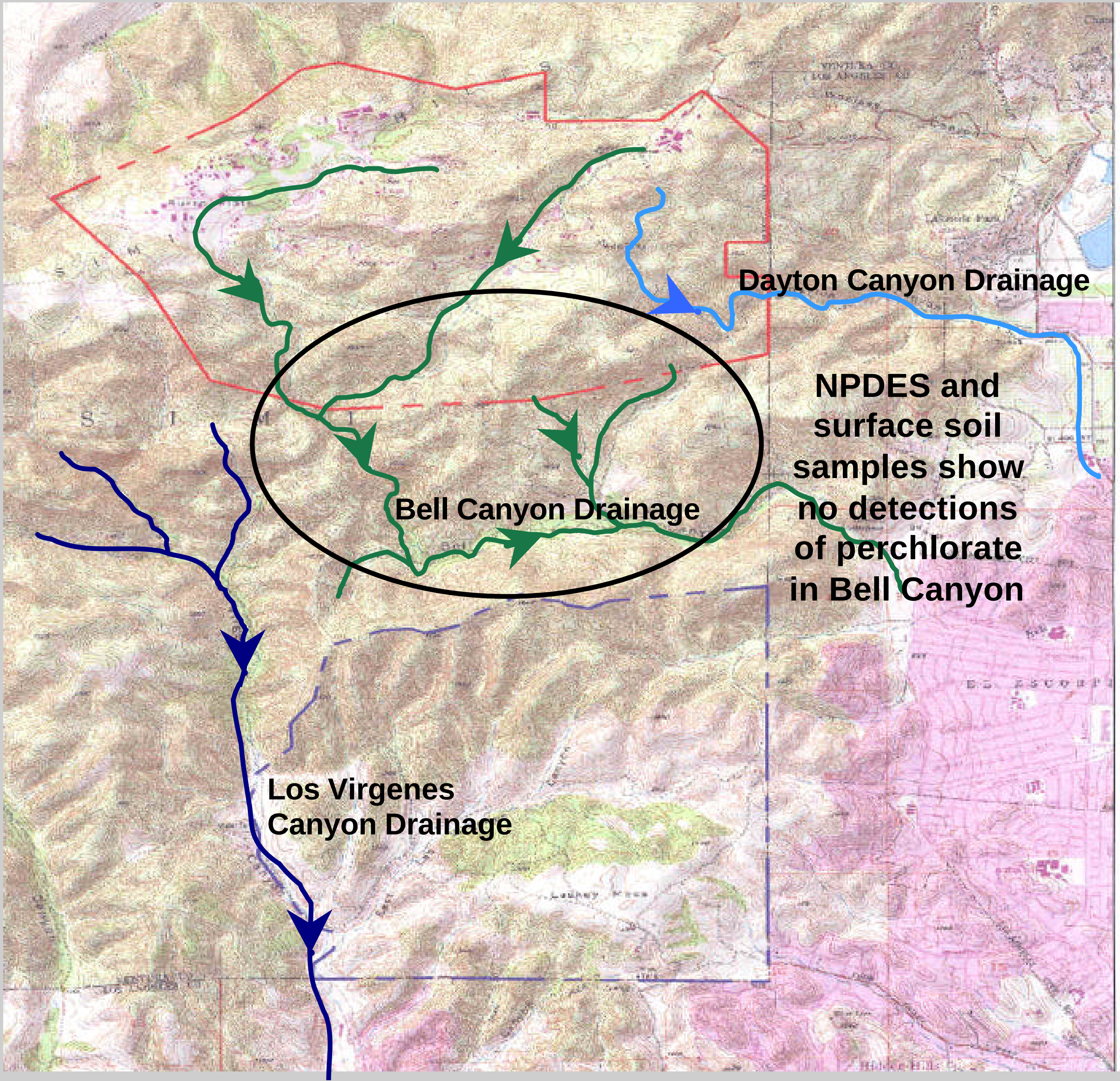
Perchlorate also detected in shallow Simi Valley groundwater upgradient of a "groundwater cascade" and above where the northern SSFL drainages empty into Arroyo Simi



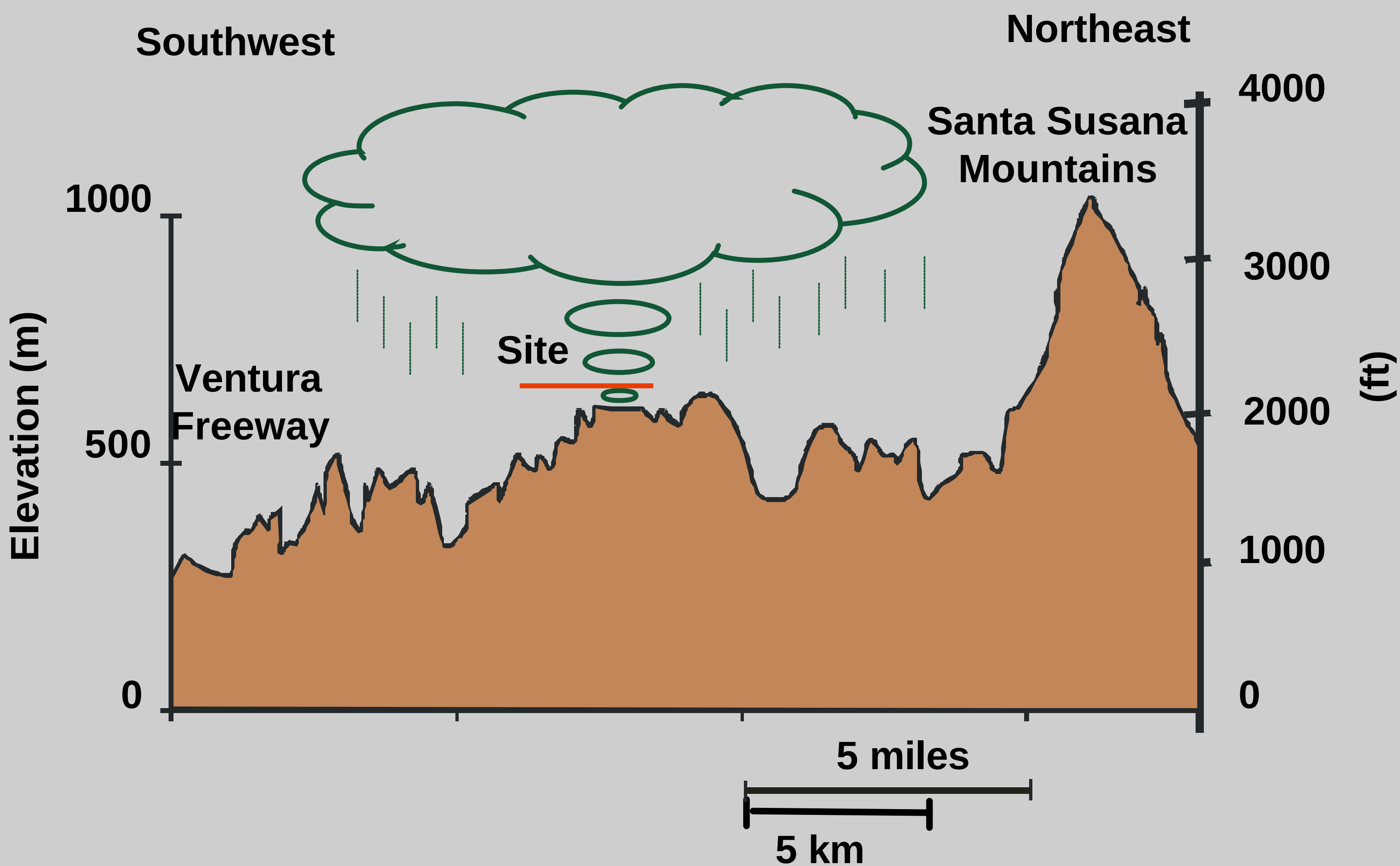
Data are inconsistent with a release from the SSFL

Surface water does not flow from the SSFL on or adjacent to the proposed Ahmanson Ranch development

Separate and distinct drainages

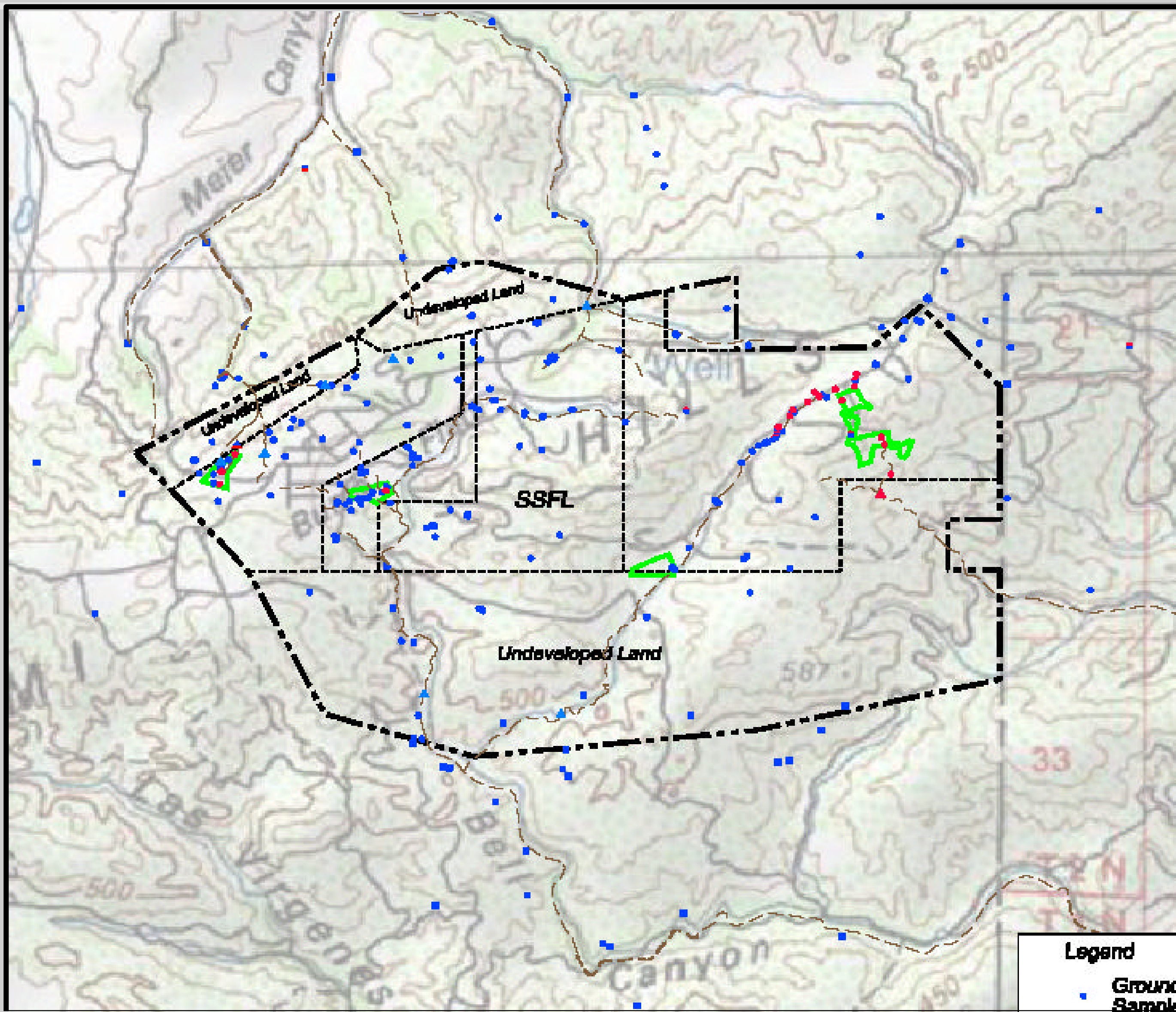


Has perchlorate been transported off of the SSFL by atmospheric deposition?

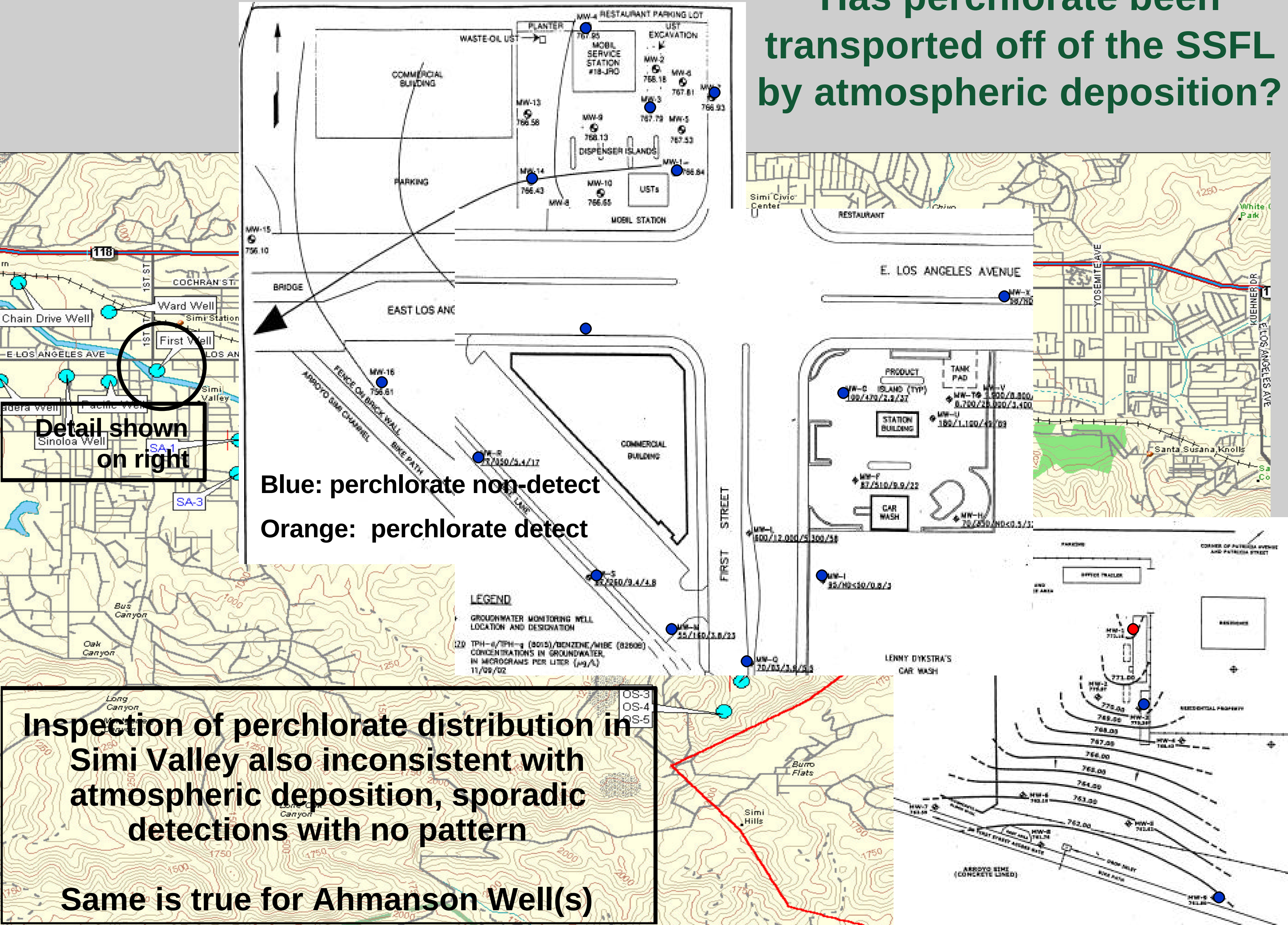


Has perchlorate been transported off of the SSFL by atmospheric deposition?

- Inspection of the distribution of perchlorate in wells located on-site <u>does not reveal a pattern consistent</u> with atmospheric deposition
- On-site detections of perchlorate are local to where perchlorate was detected in soil



Has perchlorate been transported off of the SSFL by atmospheric deposition?



Detail shown on right

Blue: perchlorate non-detect

Orange: perchlorate detect

Inspection of perchlorate distribution in Simi Valley also inconsistent with atmospheric deposition, sporadic detections with no pattern

Same is true for Ahmanson Well(s)

Has perchlorate been transported off of the SSFL by groundwater flow? If not, why is it different than almost all other perchlorate sites?

- **Requires Understanding of:**
  - **Geologic Framework - Dr. Ross Wagner**
  - **Site Conditions and Physical Properties of Bedrock on Groundwater Flow and Subsequently Chemical Transport**

Groundwater Advisory Panel

Has perchlorate been transported off of the SSFL by groundwater flow? If not, why is it different than almost all other perchlorate sites?

Significant time will be spent exploring the transport of perchlorate in groundwater

because

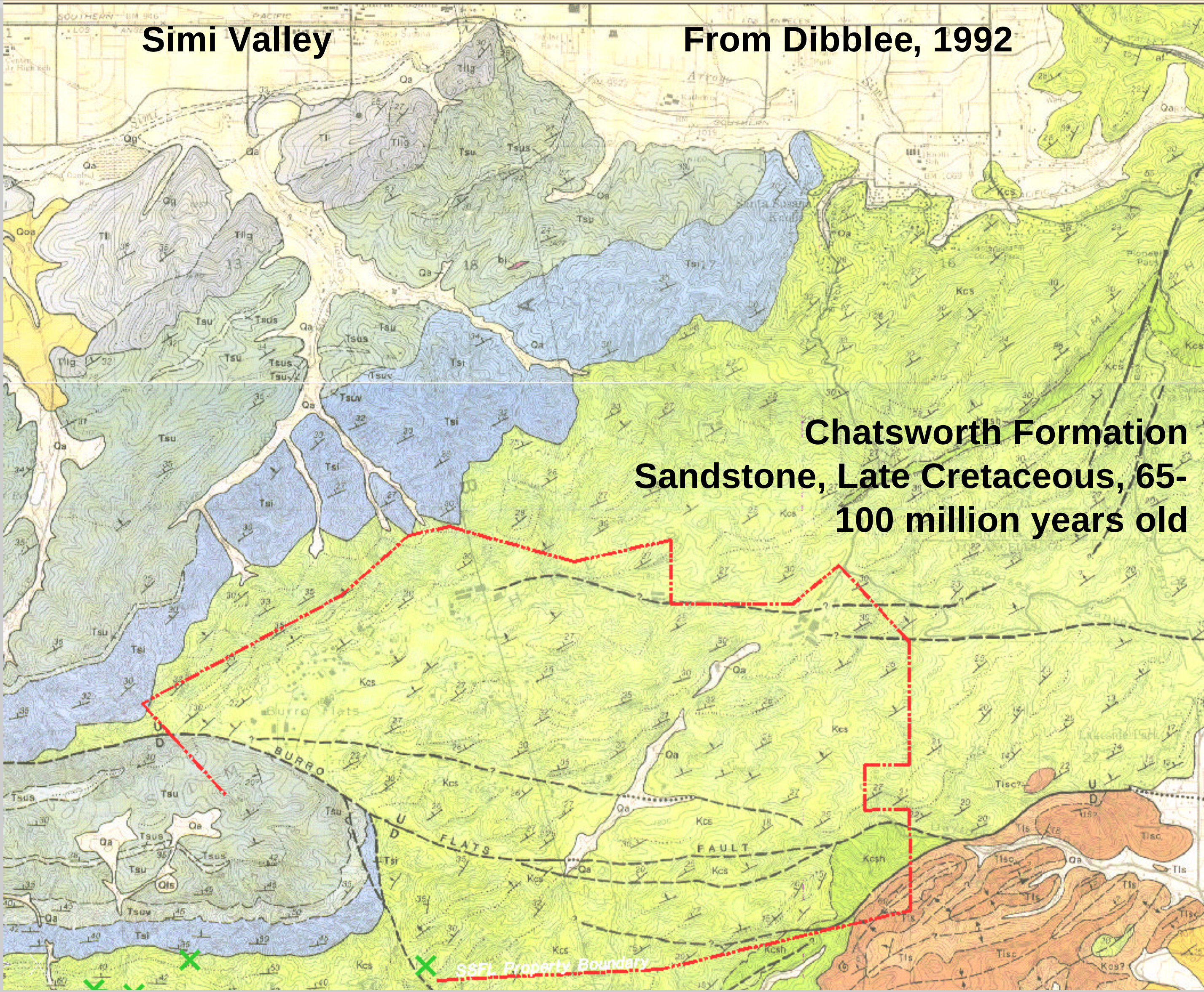
most other sites where perchlorate has been detected far away from where it was released has been through this transport pathway

How Does the Geology Influence the Groundwater Flow System?

First requires an understanding of the regional geologic setting and then:

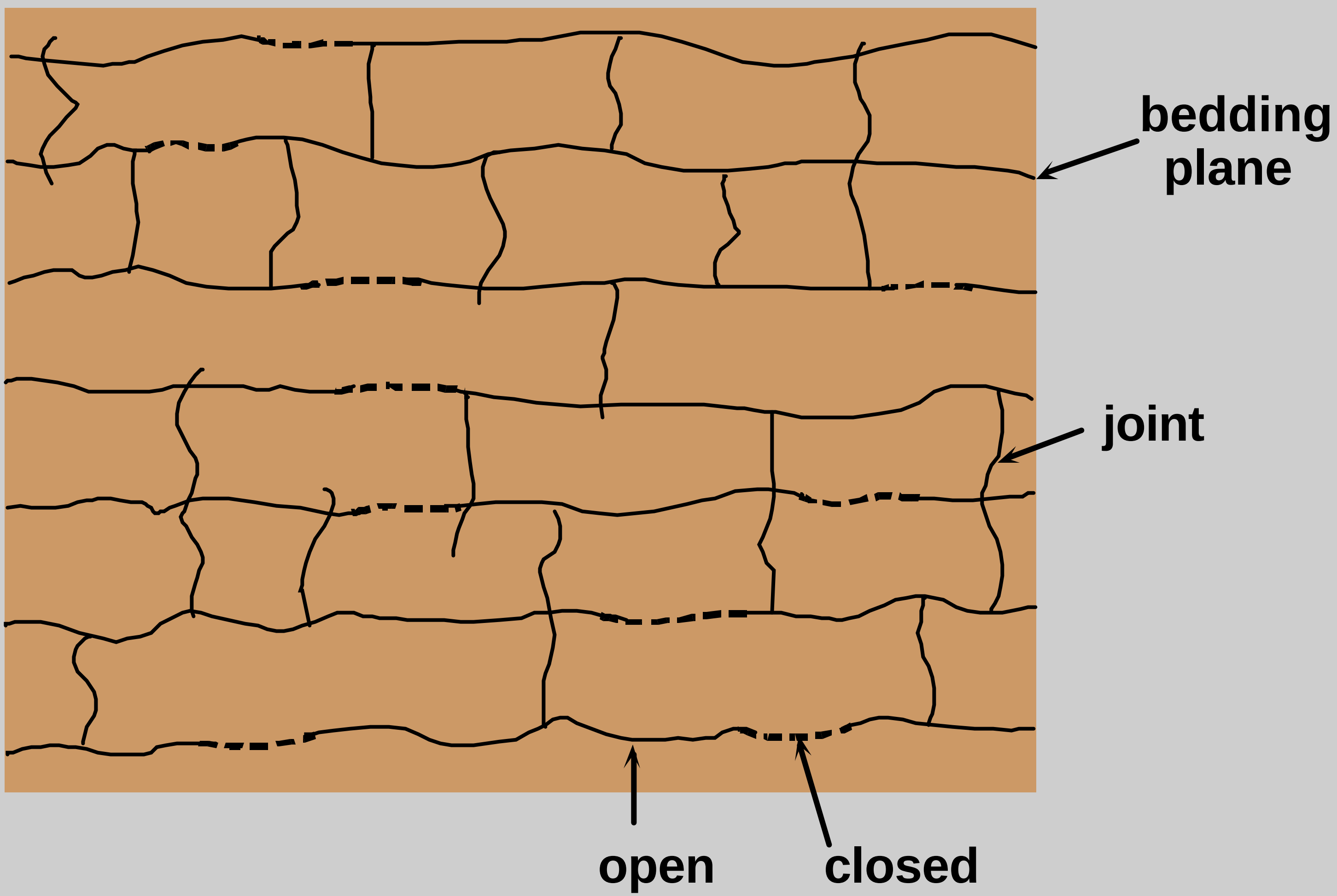
Detailed understanding of rock properties:

- joints (fractures)
- faults
- stratigraphy
- porosity
- permeability

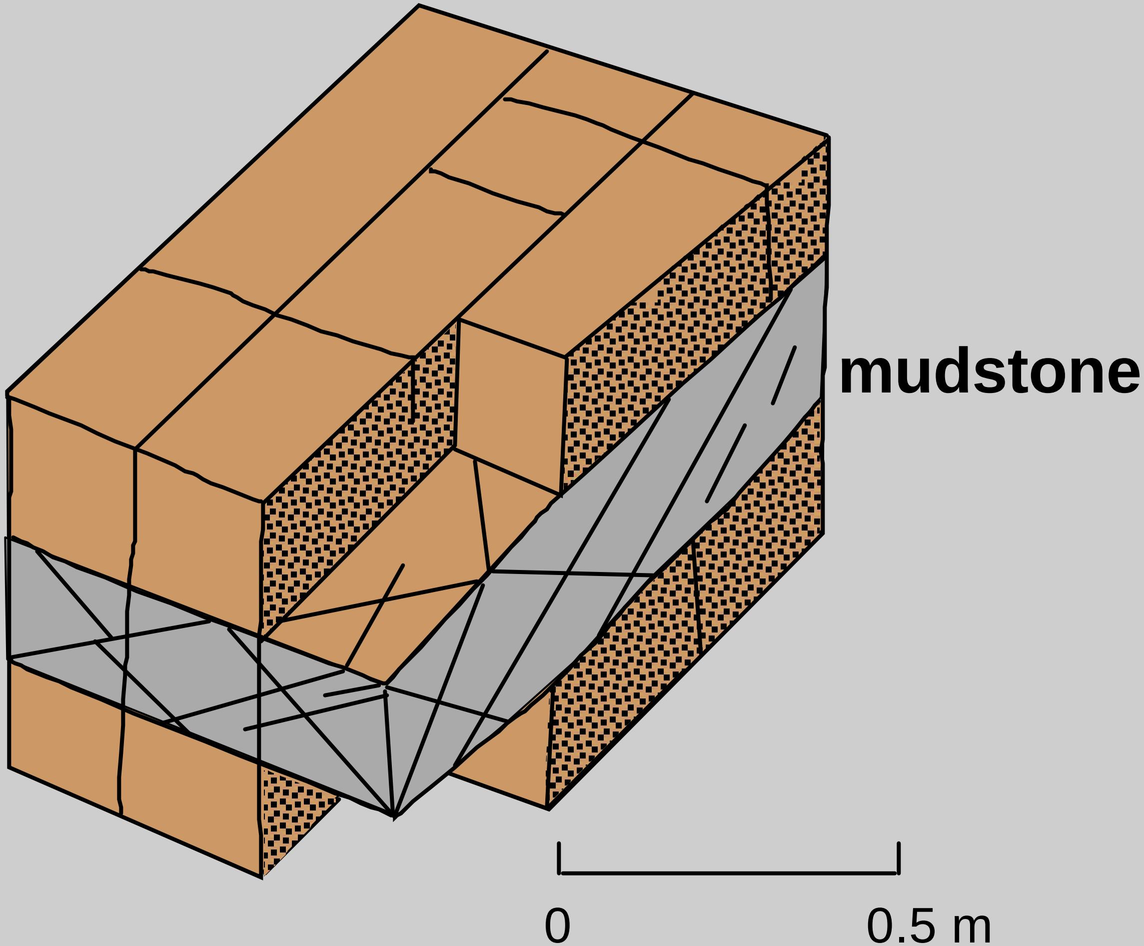


COMMON TYPES OF FRACTURES IN SEDIMENTARY ROCKS

Bedding planes and joints



Fracture System in Sandstone and Mudstone

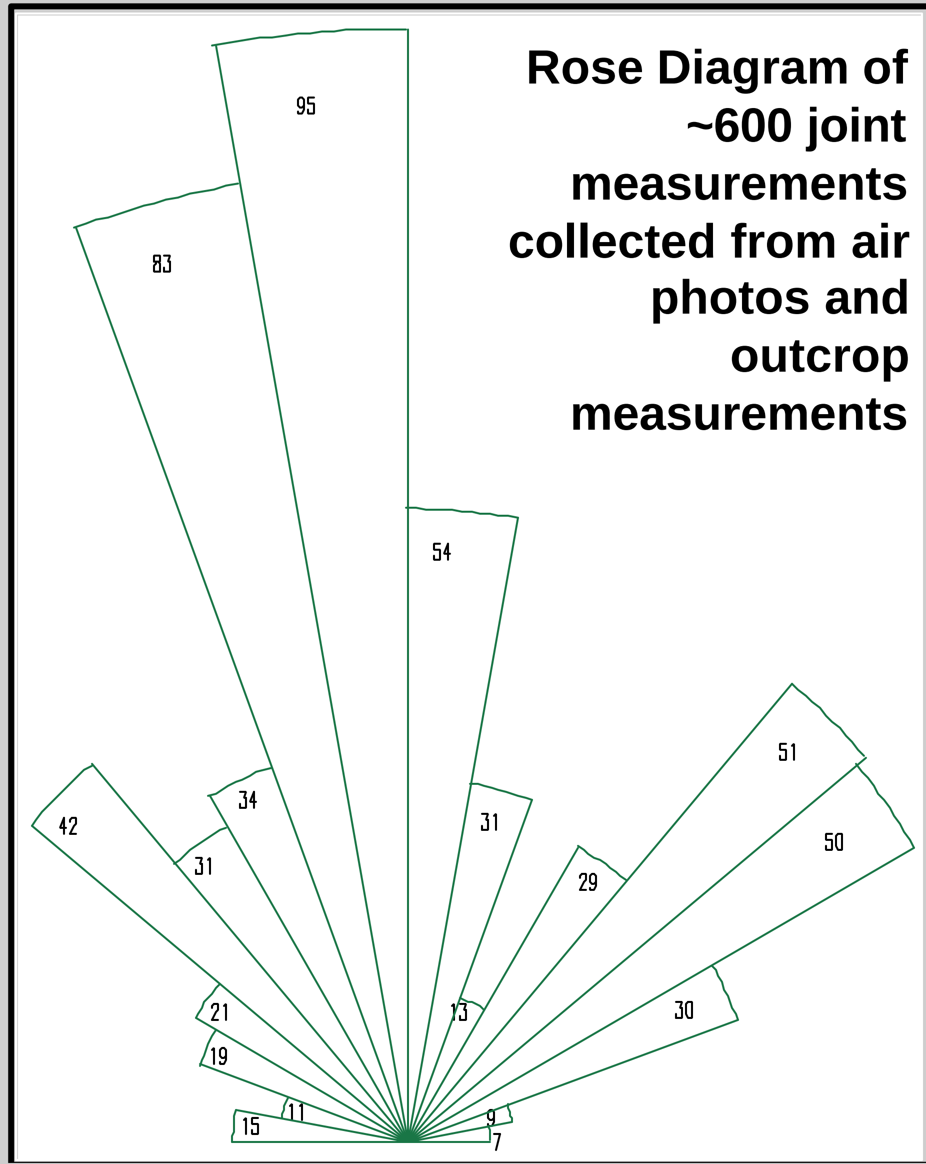


(from Chernyshev and Dearman, 1991)

Do joints direct groundwater flow in a preferred direction?

- Joint is fracture without displacement,
  - typically have preferred orientations
  - provide rapid groundwater flow paths

- Wide variety of joint orientations at the SSFL minimally influence groundwater flow directions



Photographs Reveal the Variability in Joint Orientation at/near the SSFL

On-site aerial photo

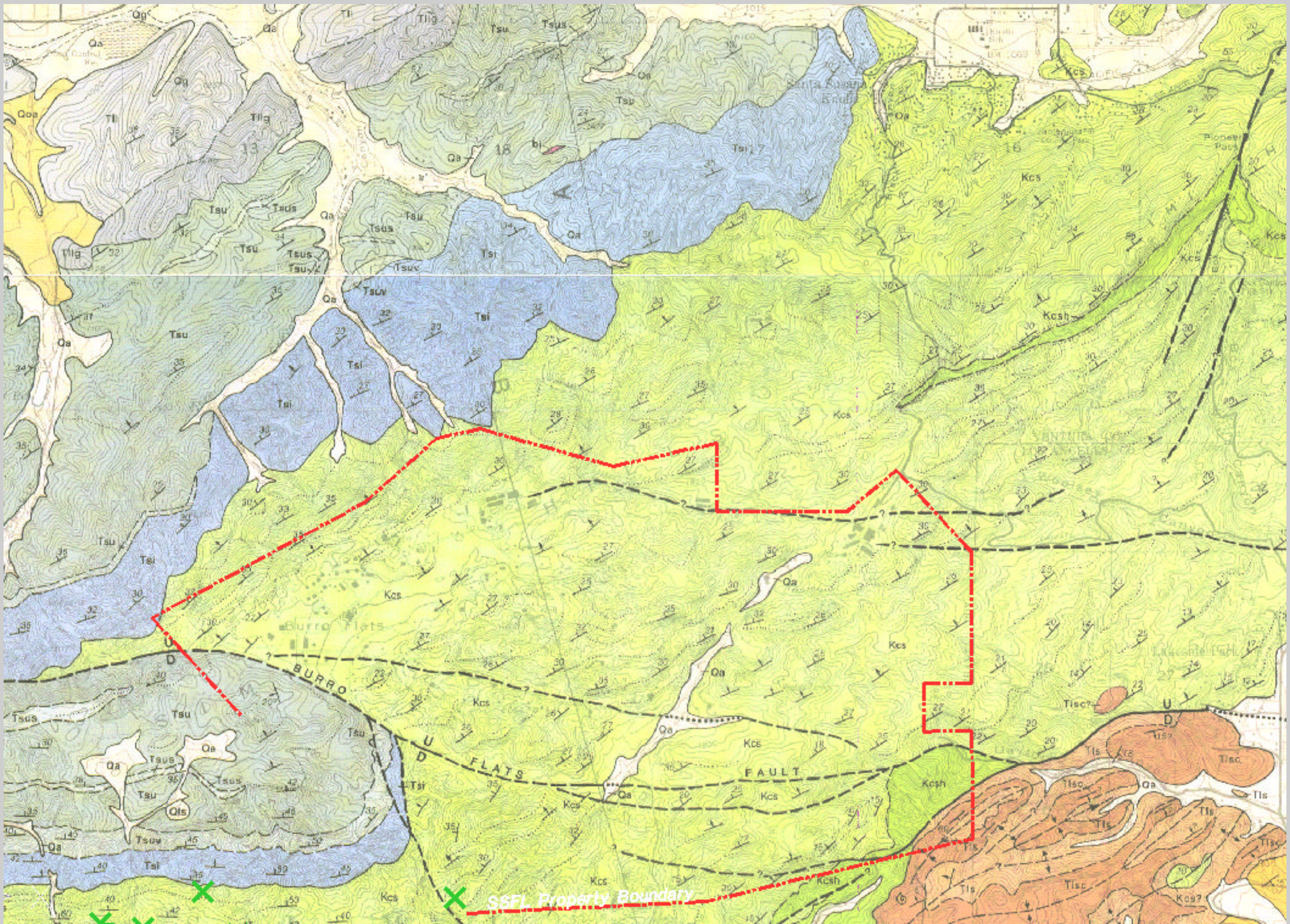
Photo on East Side of Box Canyon

Are there long through-going joints that extend for significant distances?

Inspections and photos indicate that joints stop at bedding plane boundaries and hence do not create long through-going features

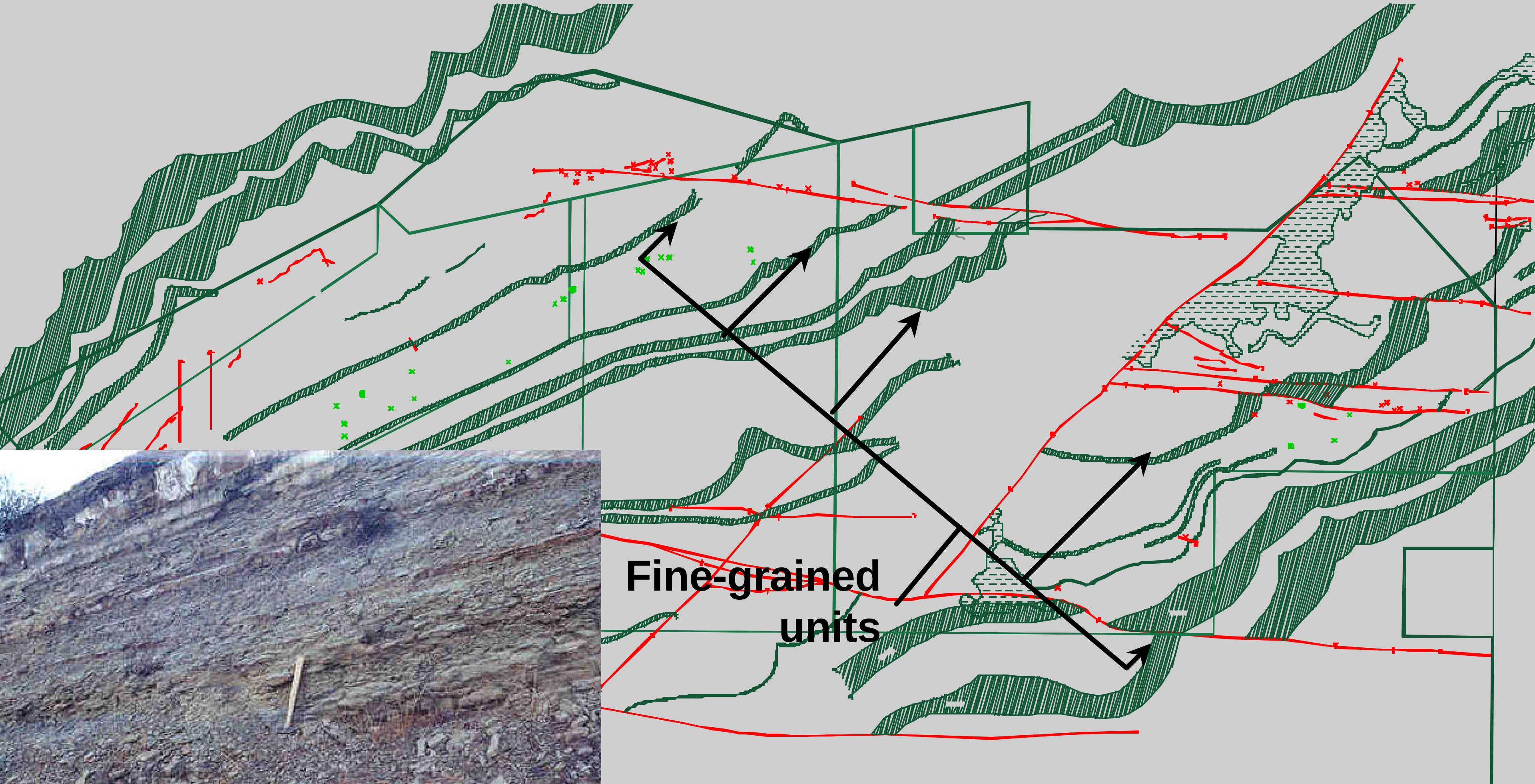
Are there any laterally extensive finer-grained features within the Chatsworth Formation? If so, do they influence groundwater flow?

Inspection of Dibblee's 1992 Geologic Map would indicate that there aren't any laterally-extensive finer-grained units within the SSFL, however..



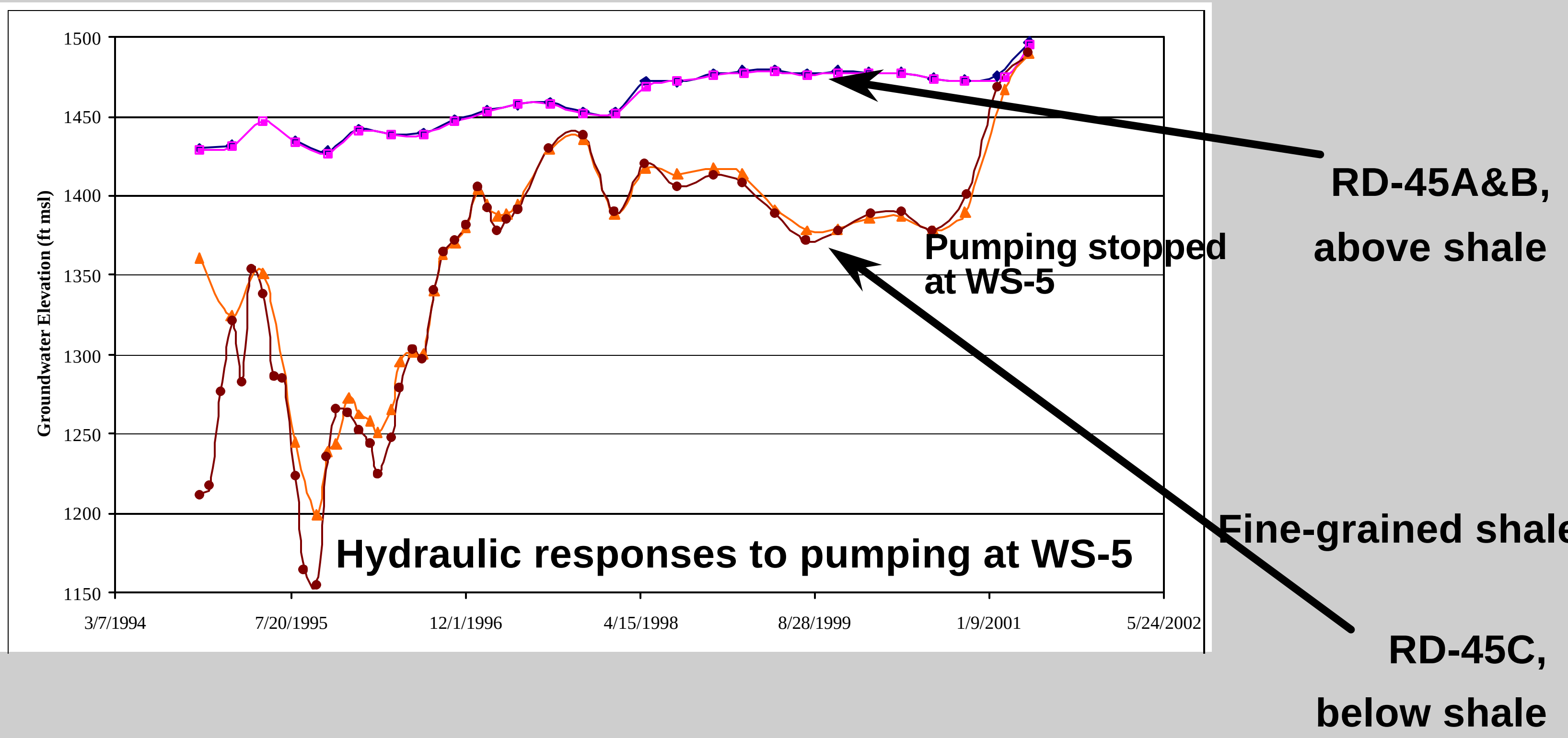
Are there any laterally extensive finer-grained features within the Chatsworth Formation?

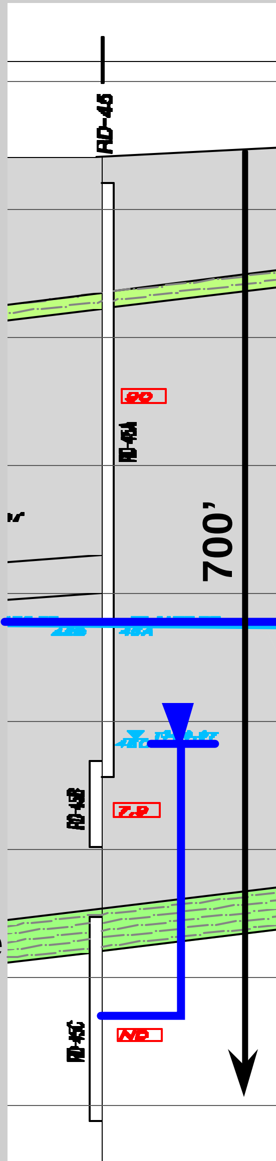
However.. Four years of field reconnaissance and analysis shows a number of finer-grained shales and siltstones present



Do the fine-grained features influence groundwater flow?

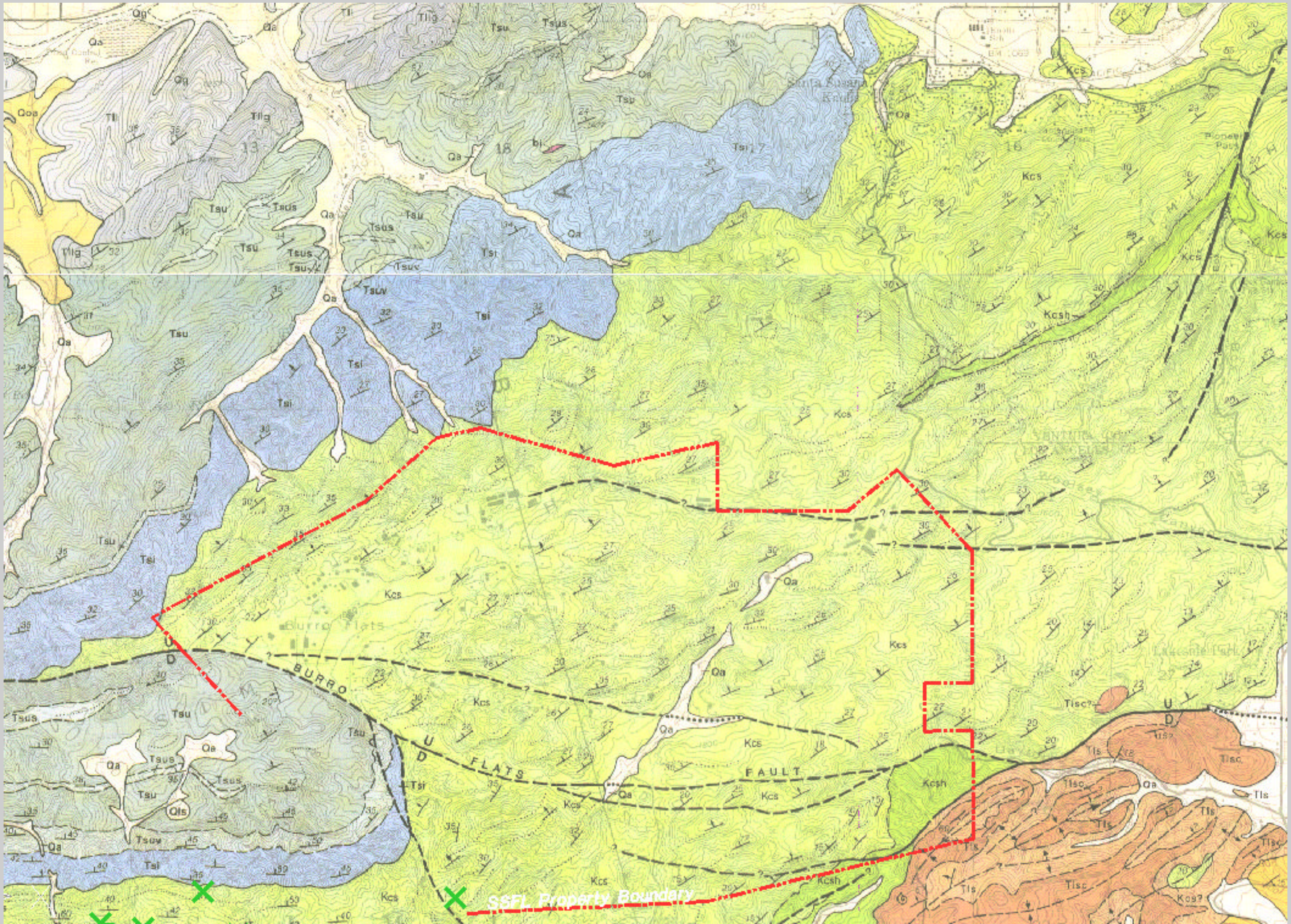
Detailed analysis of water level, hydraulic responses to pumping and chemical concentration data show that finer-grained features are aquitards that significantly influence groundwater flow and hence perchlorate transport





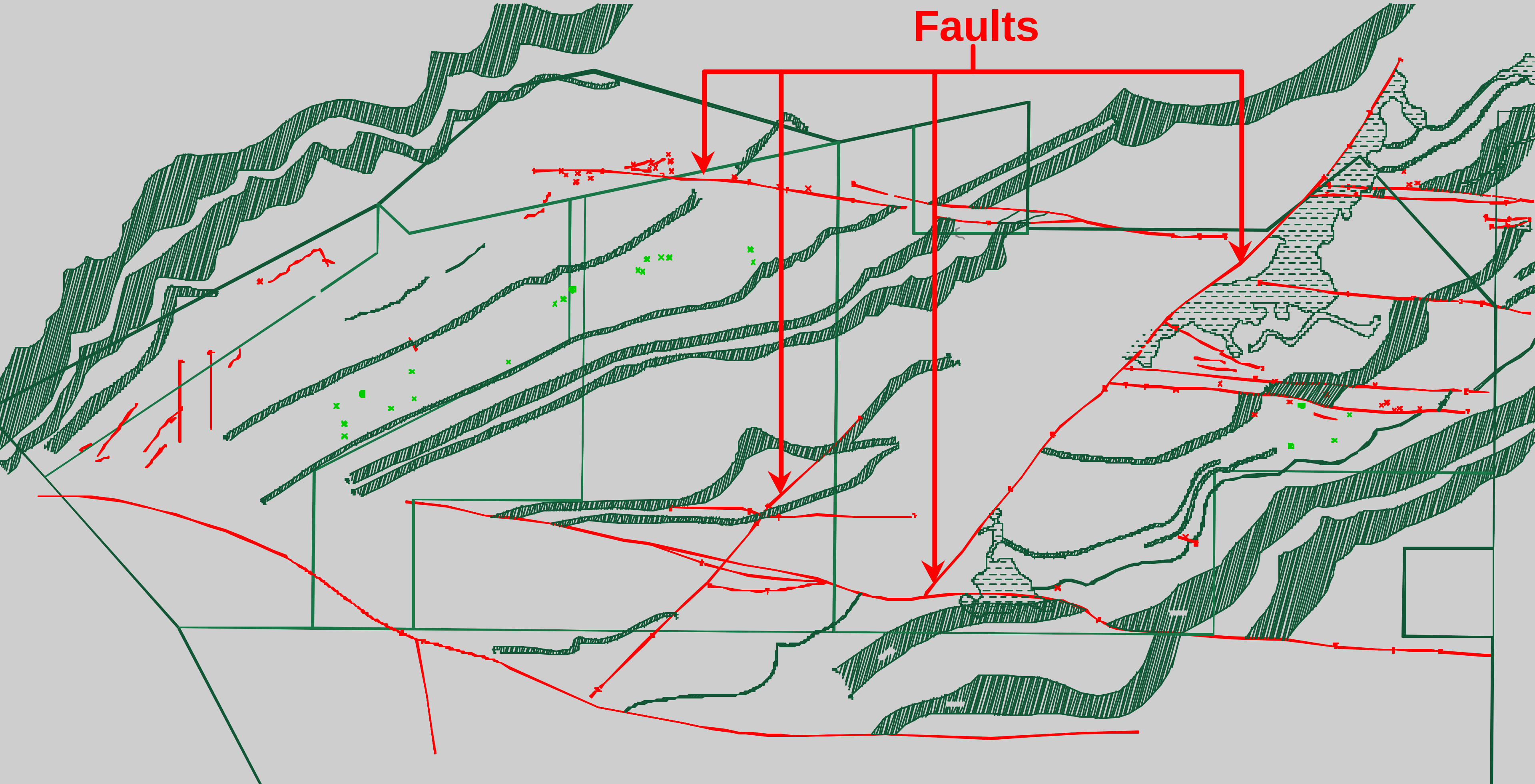
Are faults present at the SSFL within the Chatsworth Formation? If so, do they influence groundwater flow?

Inspection of Dibblee's 1992 Geologic Map shows about five faults beneath the SSFL. Most striking (running) east-west. However..



Are faults present at the SSFL within the Chatsworth Formation?

However.. Four years of field reconnaissance and analysis shows a number of additional faults present.

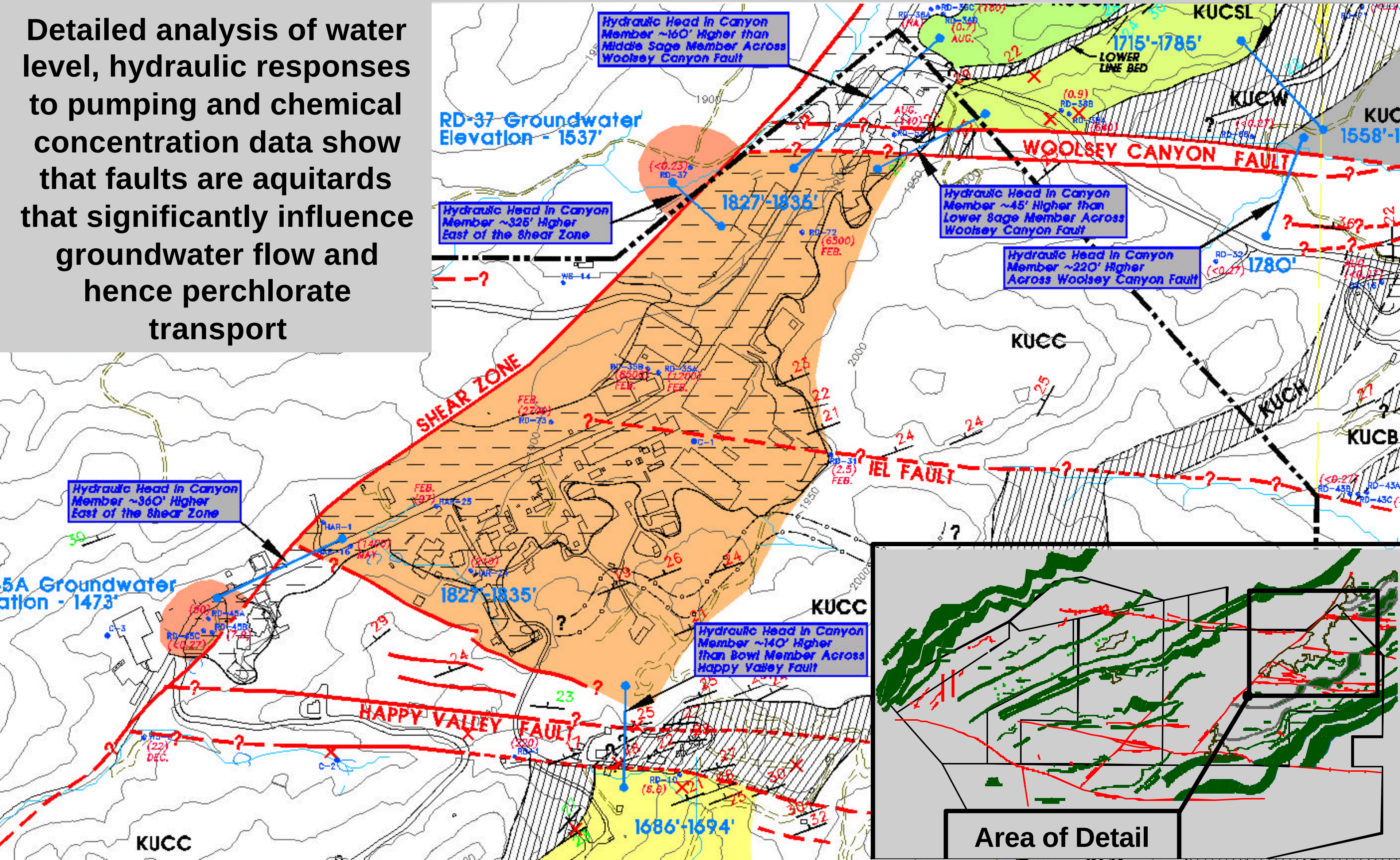


Do faults influence groundwater flow?

Detailed inspection reveals the presence of fine-grained gouge within faults

Do faults influence groundwater flow?

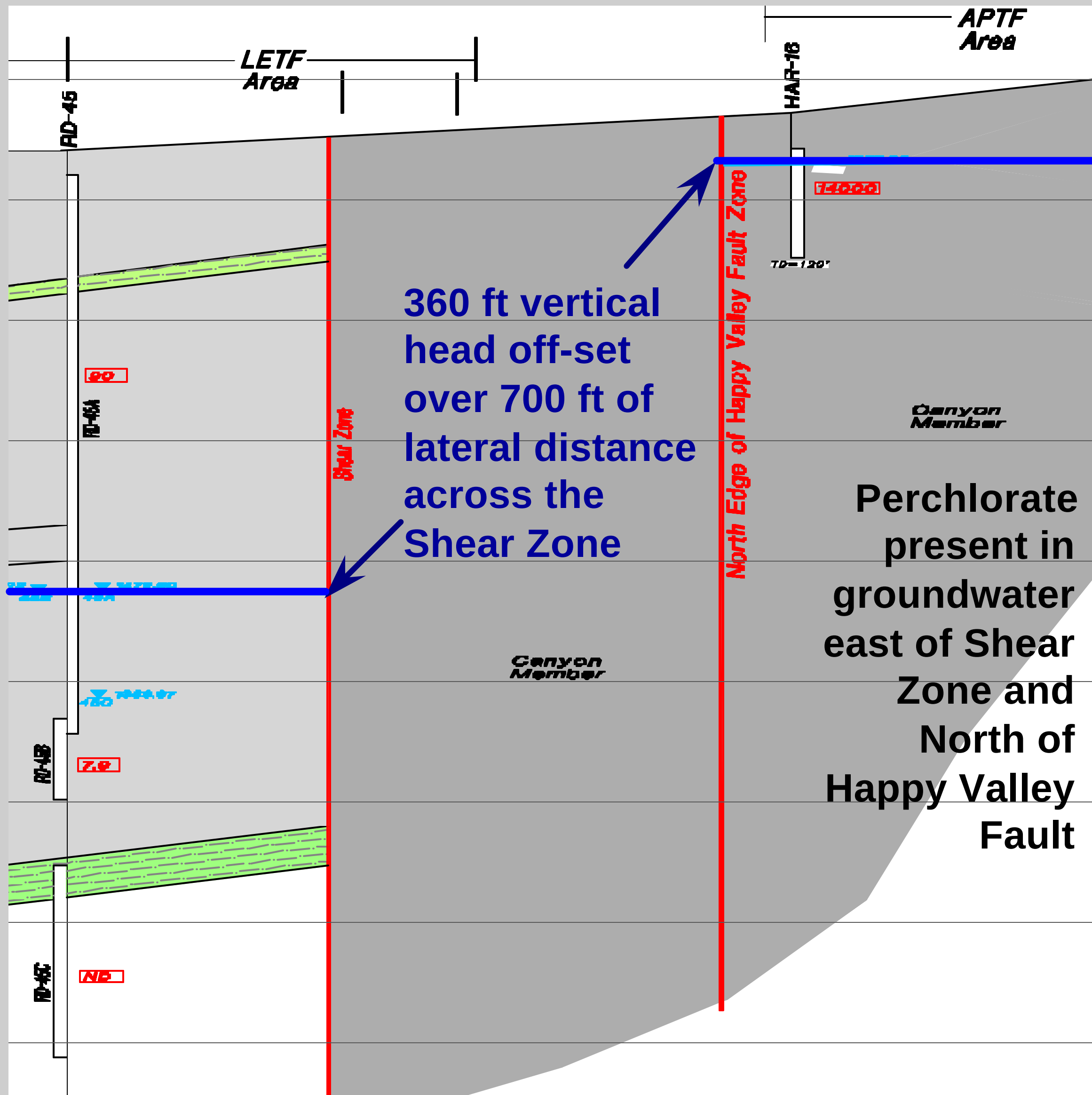
Detailed analysis of water level, hydraulic responses to pumping and chemical concentration data show that faults are aquitards that significantly influence groundwater flow and hence perchlorate transport



Do faults influence groundwater flow?

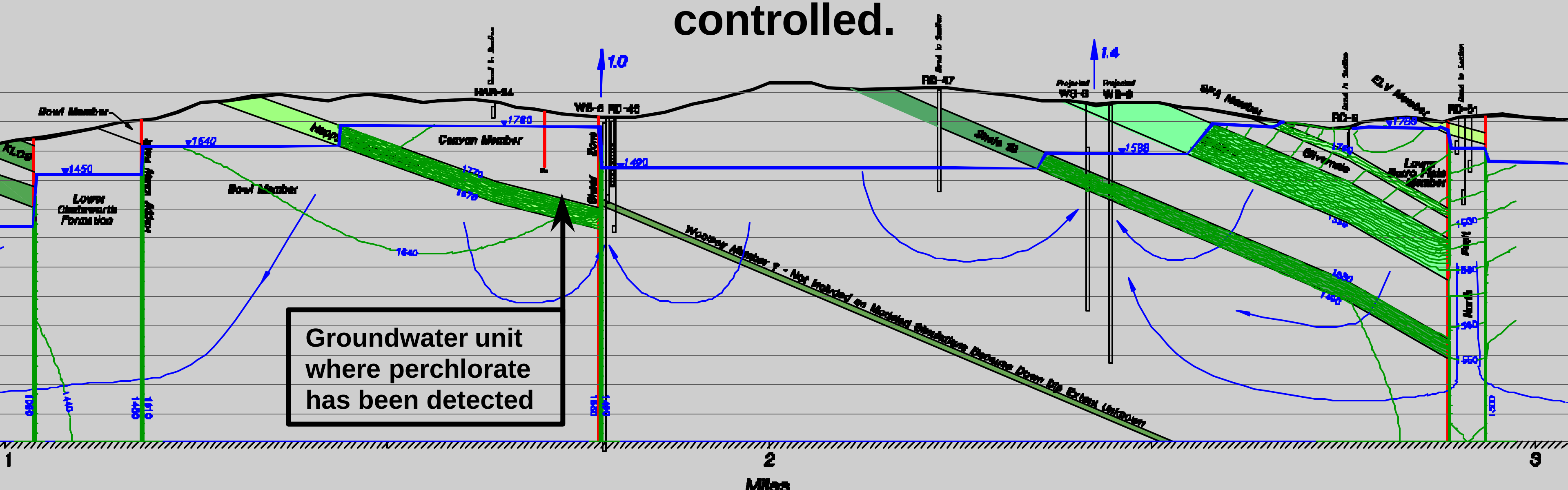
Detailed analysis of water level, hydraulic responses to pumping and chemical concentration data show that faults are aquitards that significantly influence groundwater flow and hence perchlorate transport.

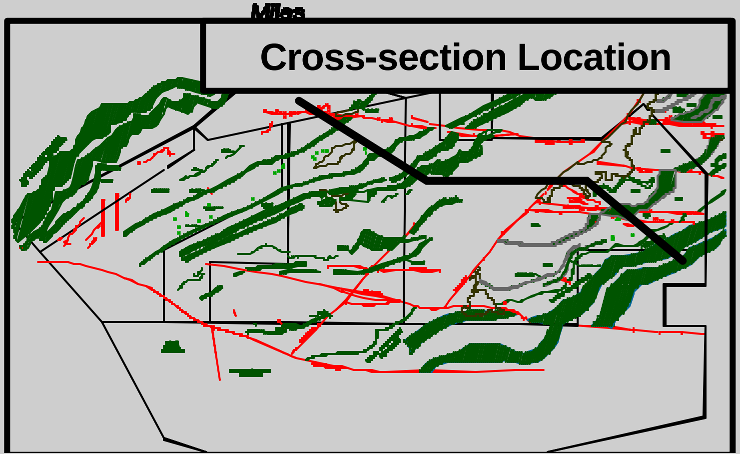
Faults, coupled with fine-grained stratigraphic members effectively hydraulically isolate perchlorate in groundwater.



Has historical groundwater pumping at the SSFL influenced the flow system?

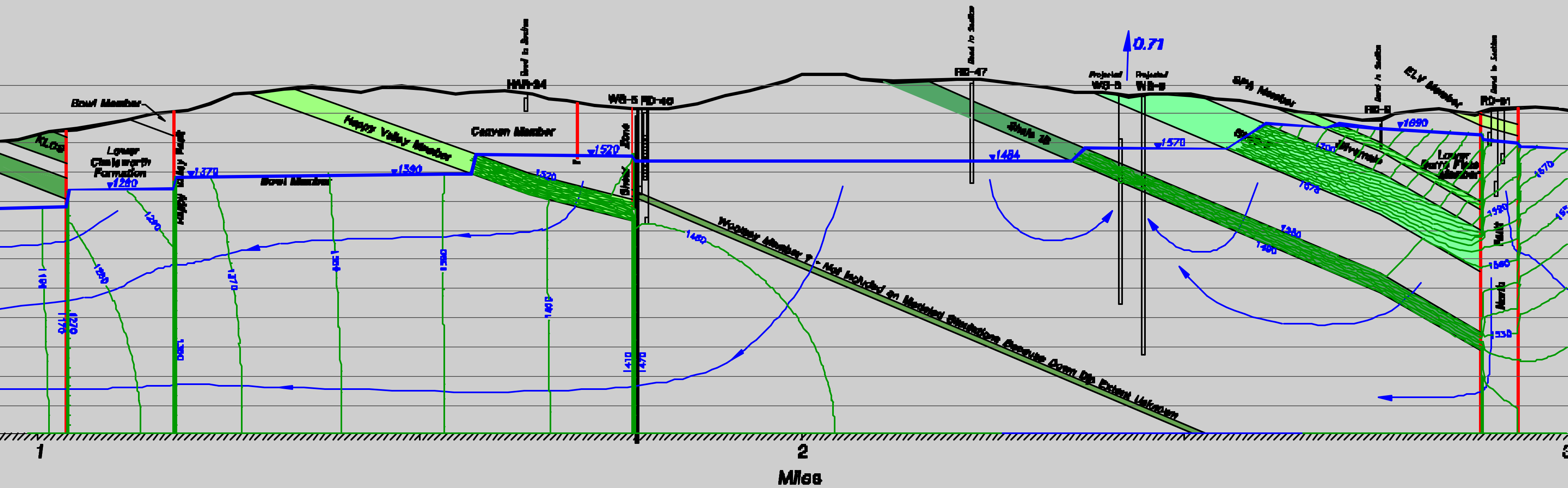
Yes. Results of 2-dimensional vertical groundwater flow simulations show that groundwater impacted with perchlorate has been hydraulically controlled.





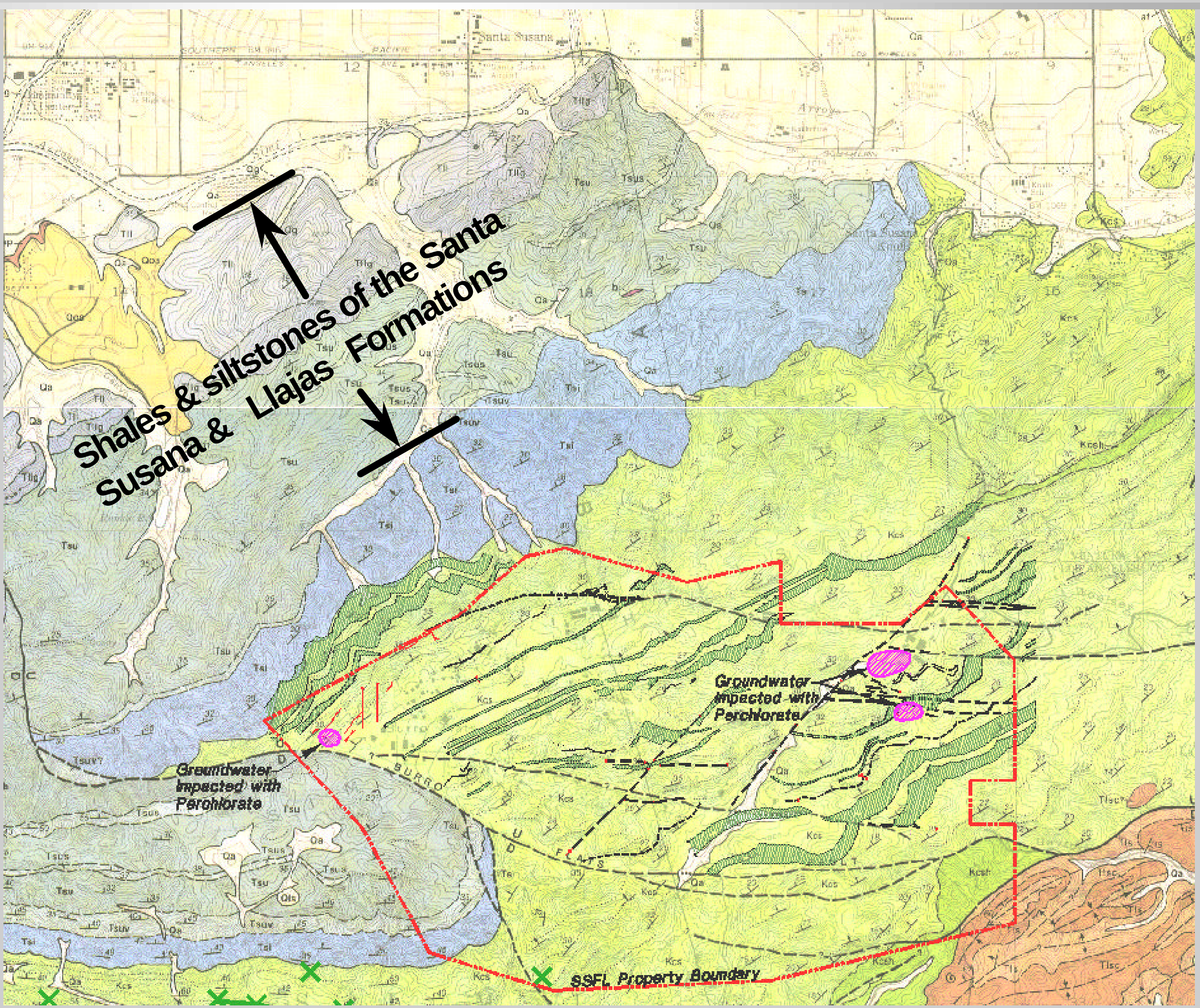
Could faults be more permeable?

2-Dimensional groundwater flow simulations show that if the permeability of the faults are increased then groundwater pumping rates can't be sustained and water table is much deeper than that measured at the SSFL.



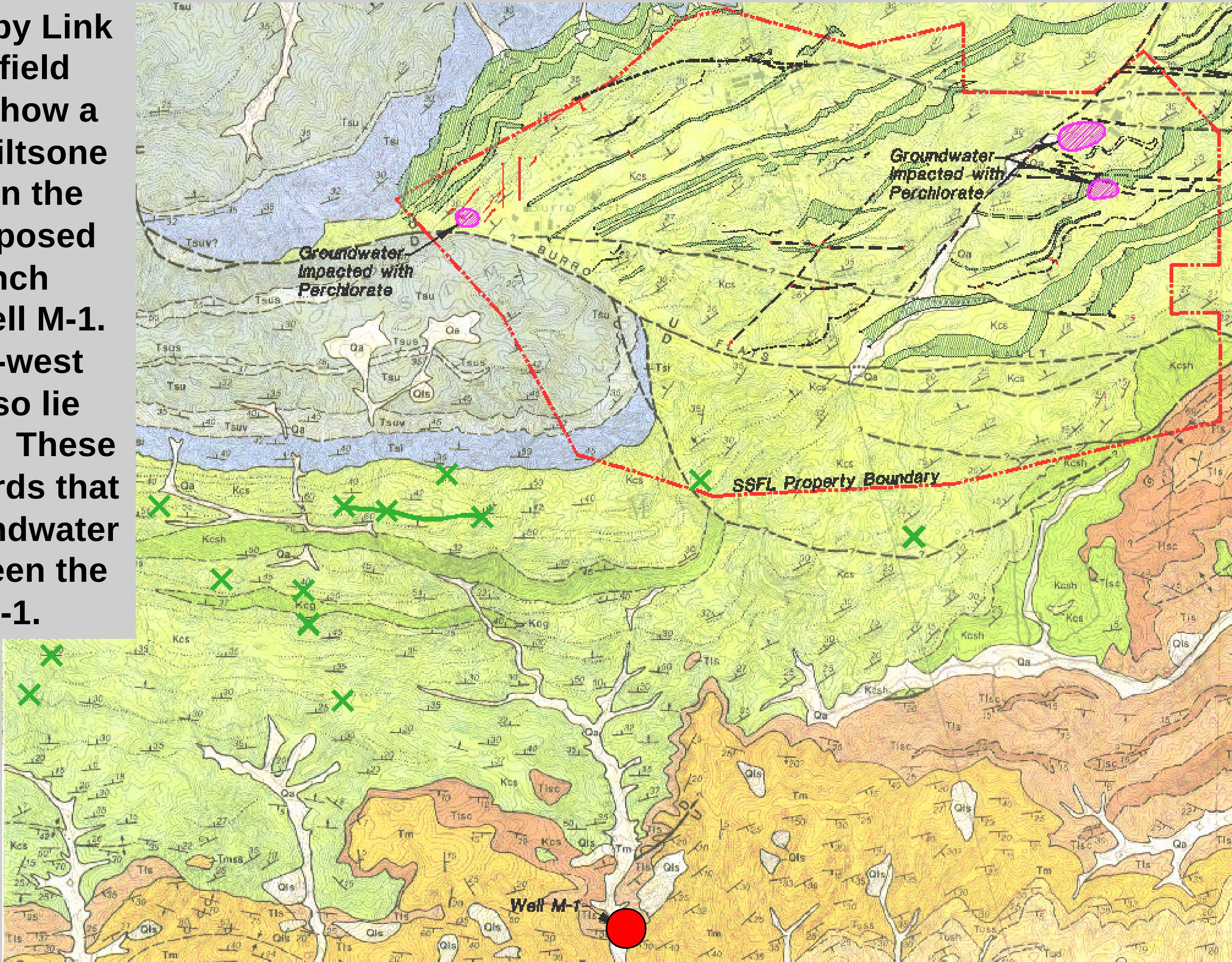
Are there fine-grained units and faults between the SSFL, Simi Valley and Ahmanson Ranch that will significantly influence the groundwater flow system?

Approximately 3,000 feet of siltstones and shales lie between the northern boundary of the SSFL and Simi Valley, creates aquitards that influence the groundwater flow system



Are there fine-grained units and faults between the SSFL, Simi Valley and Ahmanson Ranch that will significantly influence the groundwater flow system?

Work reported on by Link et al and a brief field reconnaissance show a number of shale/siltsone members between the SSFL and the proposed Ahmanson Ranch Development & well M-1. At least two east-west striking faults also lie south of the SSFL. These features are aquitards that influence the groundwater flow system between the SSFL & well M-1.



Summary of how the geology beneath the SSFL influences the groundwater flow system

- **Joint orientations minimally influence the groundwater flow system**
- **Joints stop at bedding plane boundaries and do not create long through-going features**
- **Fine-grained members and faults significantly influence the groundwater flow system**
  - **Large differences in hydraulic head**
  - **Large differences in chemical occurrence and/or concentration**
  - **Responses to pumping**
- **A number of fine-grained units and or faults lie between the SSFL, Simi Valley and Ahmanson Ranch**

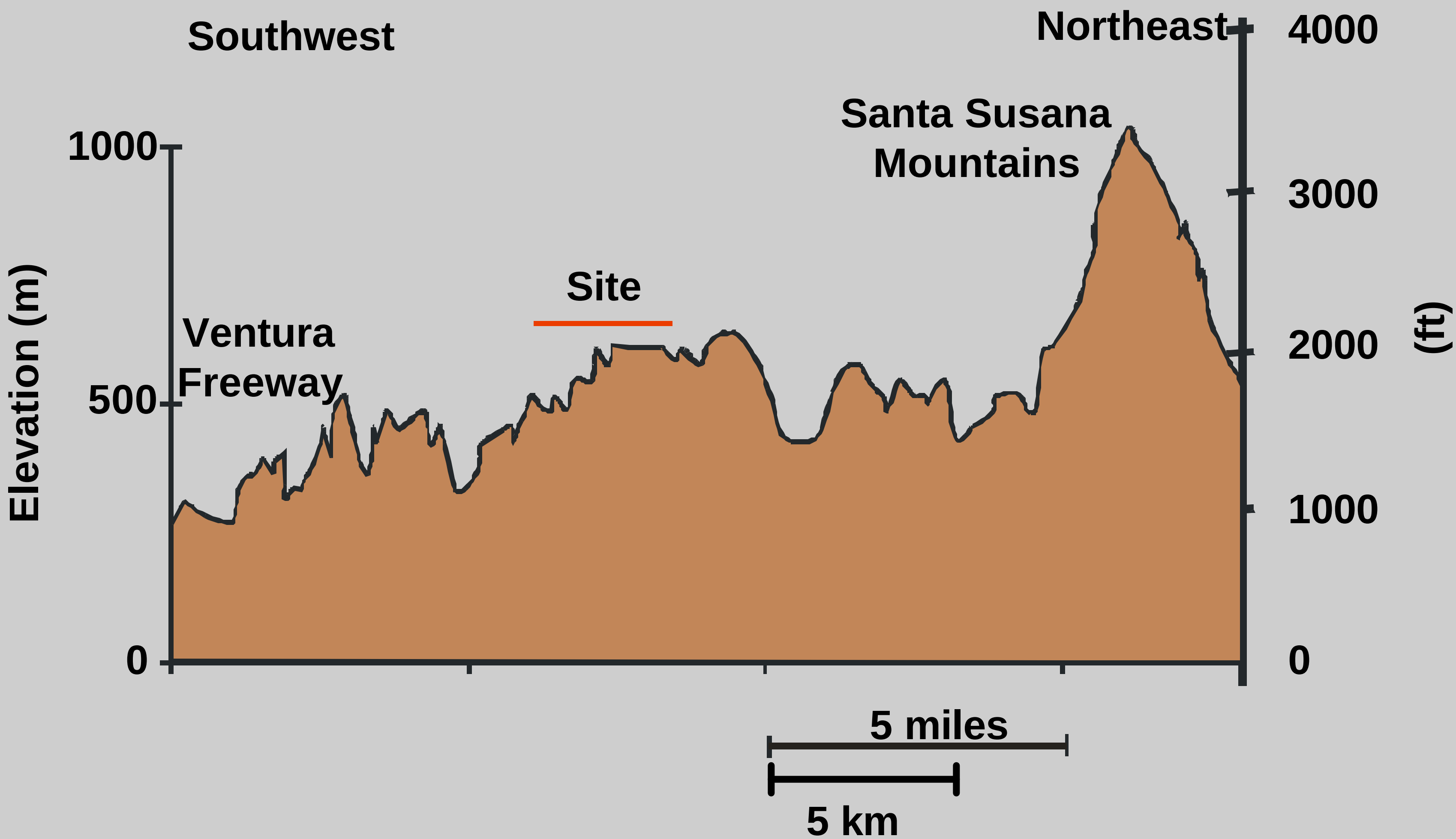
Why is the transport of perchlorate at SSFL different than almost all other perchlorate sites in California?

Groundwater Advisory Panel

Presented by:

Dr. John Cherry

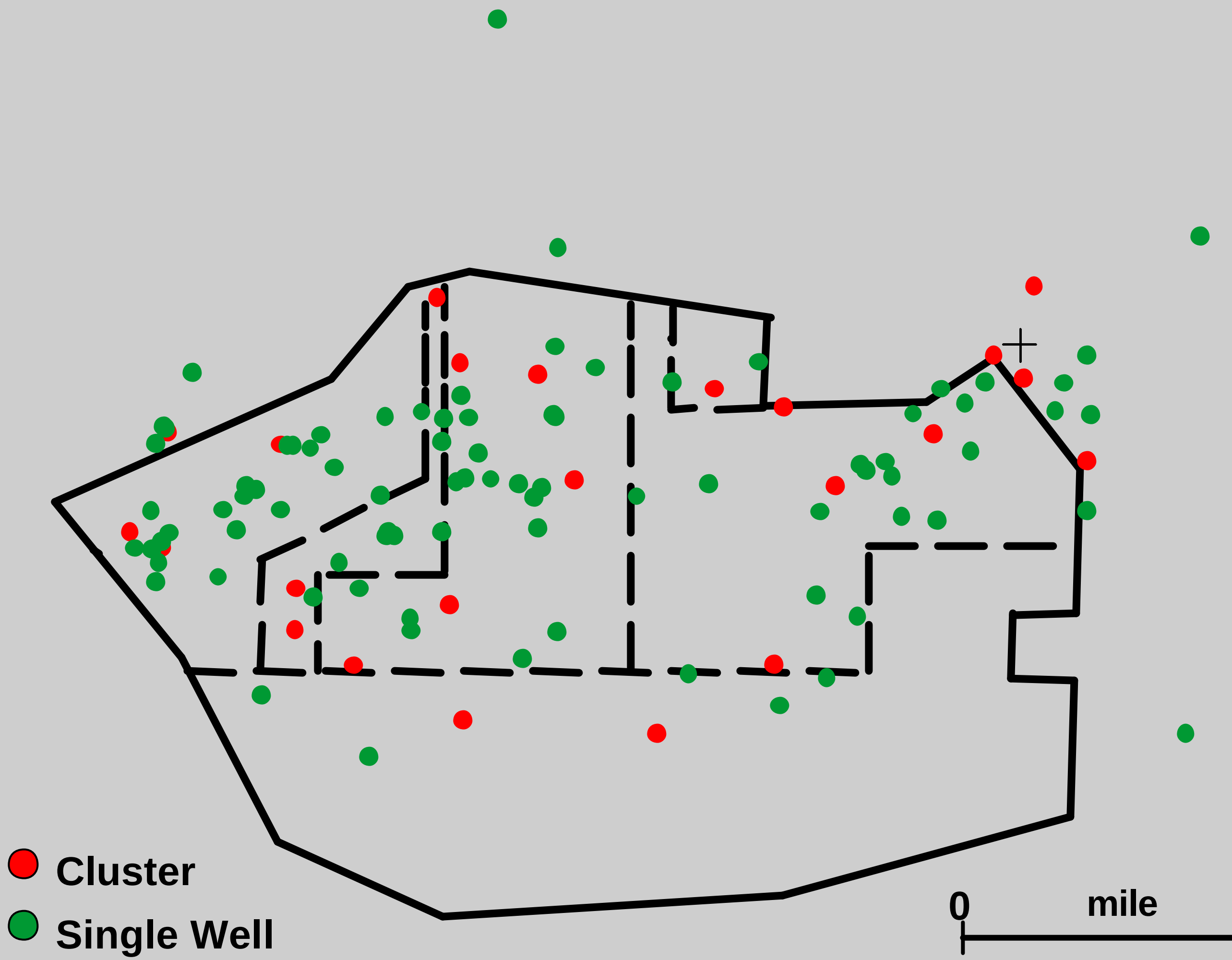
Regional Cross Section



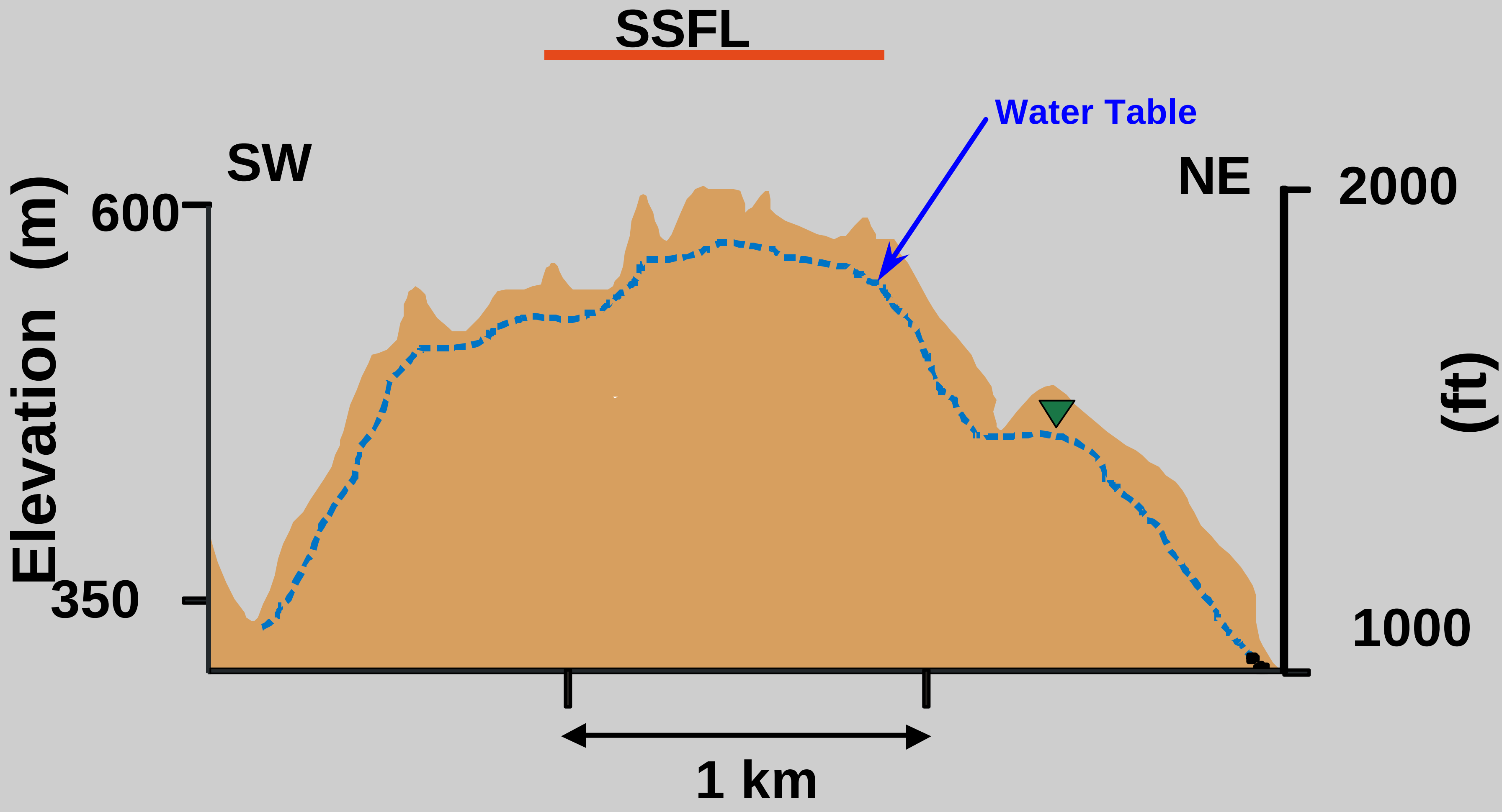
<u>One Hypothesis</u>: General View from a Distance Suggests Many Fractures, Large Permeability

→ Deep Water Table, Rapid Transport

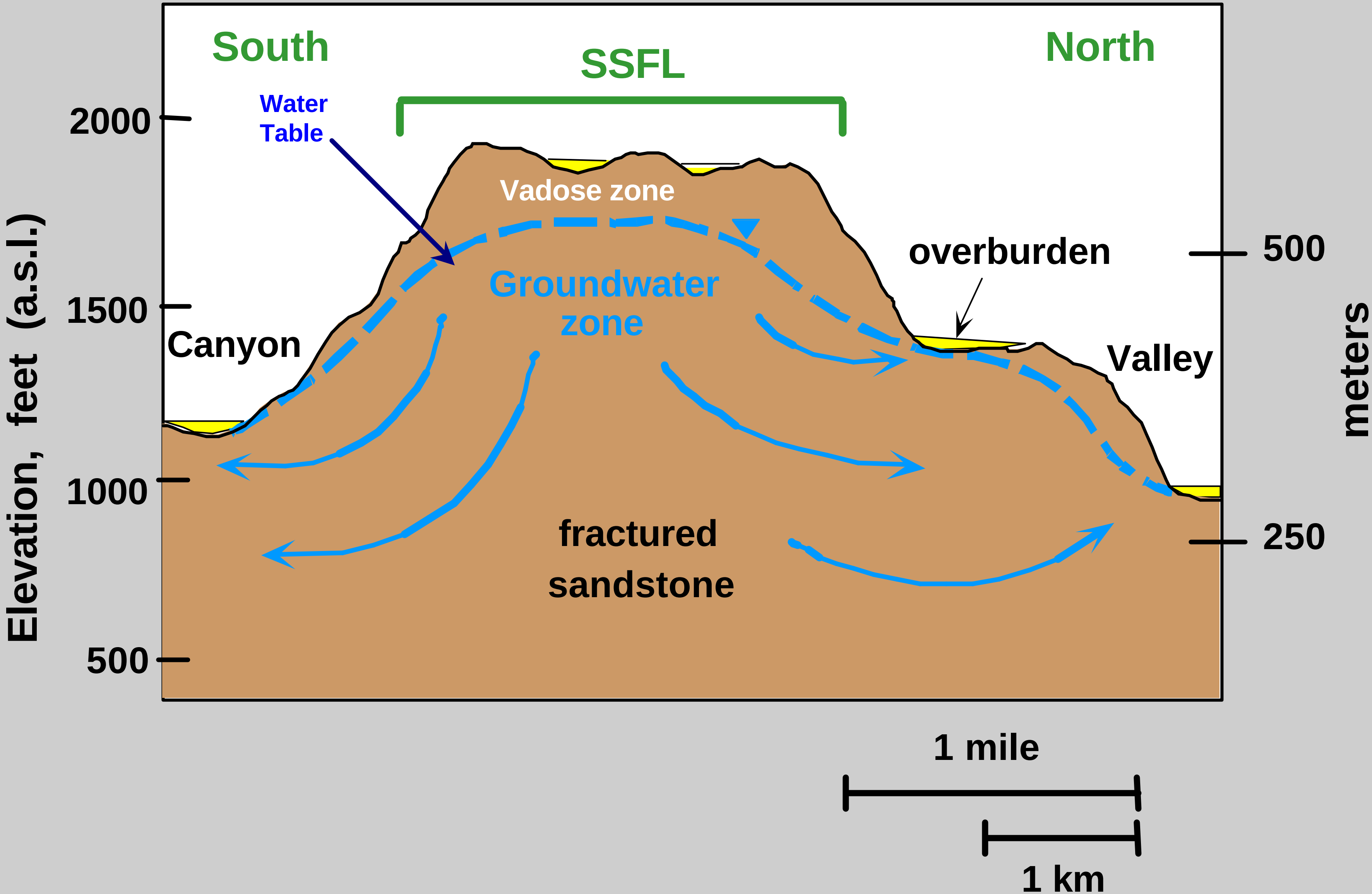
~140 Bedrock Wells Provide Lots of Information on Depth to Water in 1996



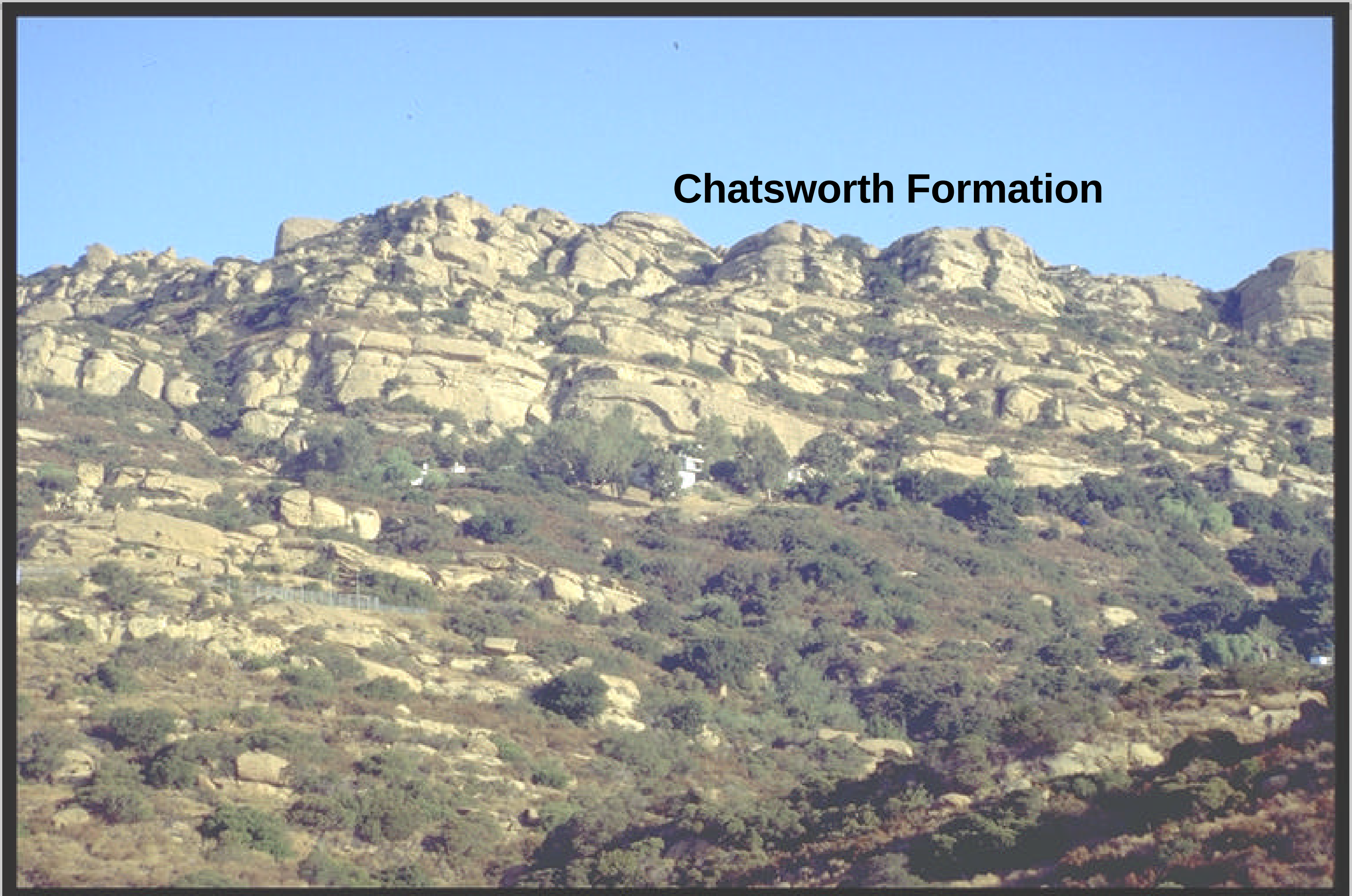
Wells Show Shallow Water Table Contradicts Initial Impression



High Water Table and Low Precipitation Means Low Bulk Hydraulic Conductivity for Mountain



Closer Inspection Revealed
Many Fractures, Shallow Water Table,
→ Low Permeability, Slow Transport at SSFL



Groundwater Principles

Darcy's Law

q=volume of flow per unit area per unit time

q=Ki

Hydraulic gradient

Hydraulic conductivity

Typical hydraulic conductivities of unlithified media in cm/s

sand	10^{-2}
silt	10^{-5}
clay	10^{-8}

Groundwater Principles

Groundwater Velocity ($\bar{v}$)

v=groundwater travel distance per unit time

$$\frac{q}{f} = \frac{Ki}{f} = \bar{v}$$

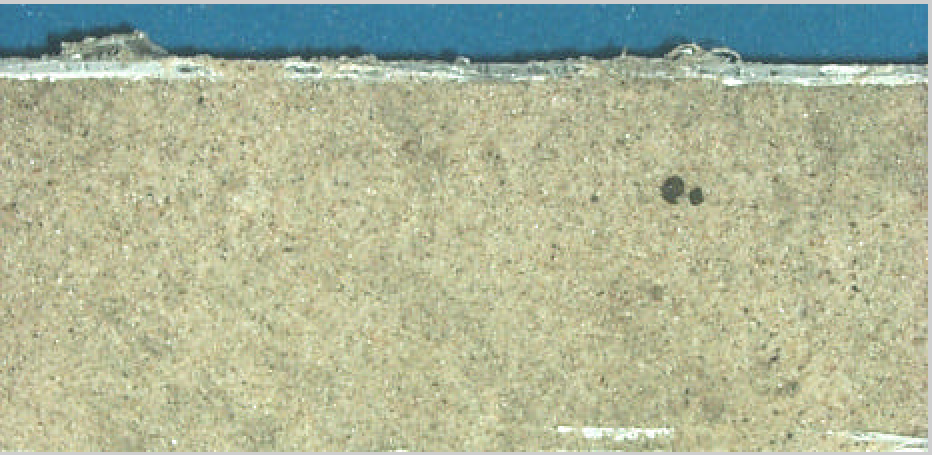
<u>Typical porosities</u> f

sand/silt/clay: 0.2- 0.4

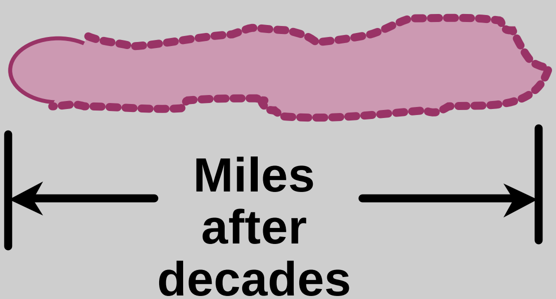
fractured rock: 0.0001

Long Perchlorate Plumes are Often the Expectation in Porous Granular Aquifers

Sand Aquifer

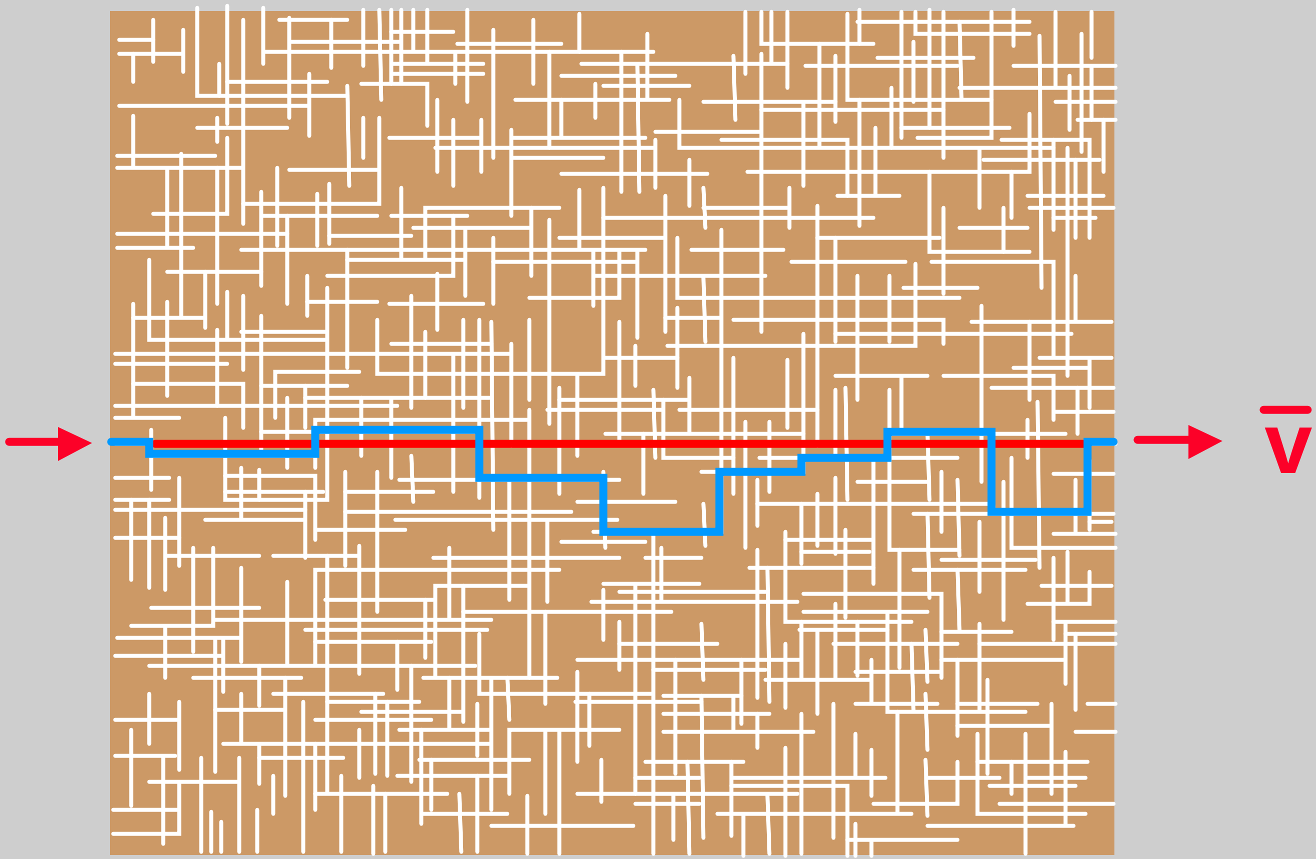


Perchlorate plume in sand, rate of travel same as groundwater



Fractured Chatsworth Formation

Average Linear Groundwater Velocity



$$\bar{v} = \frac{K_b\,[\Delta h / \Delta L]}{f_f}$$

where f_f = bulk fracture porosity

K_b = bulk hydraulic conductivity

Calculations Show Average Linear Groundwater Velocity in Moderately Permeable Sandstone to be High

$$\bar{V} = \frac{\text{Darcy Flux}}{\text{Fracture Porosity}} = \frac{K_b\,(dh/dL)}{f_f}$$

K	10^{-4} cm/s
dh/dL	0.01
f_f	0.001

$\bar{v}$ » 1000 feet per year

AVERAGE LINEAR GROUNDWATER VELOCITY
Moderately Permeable Sandstone

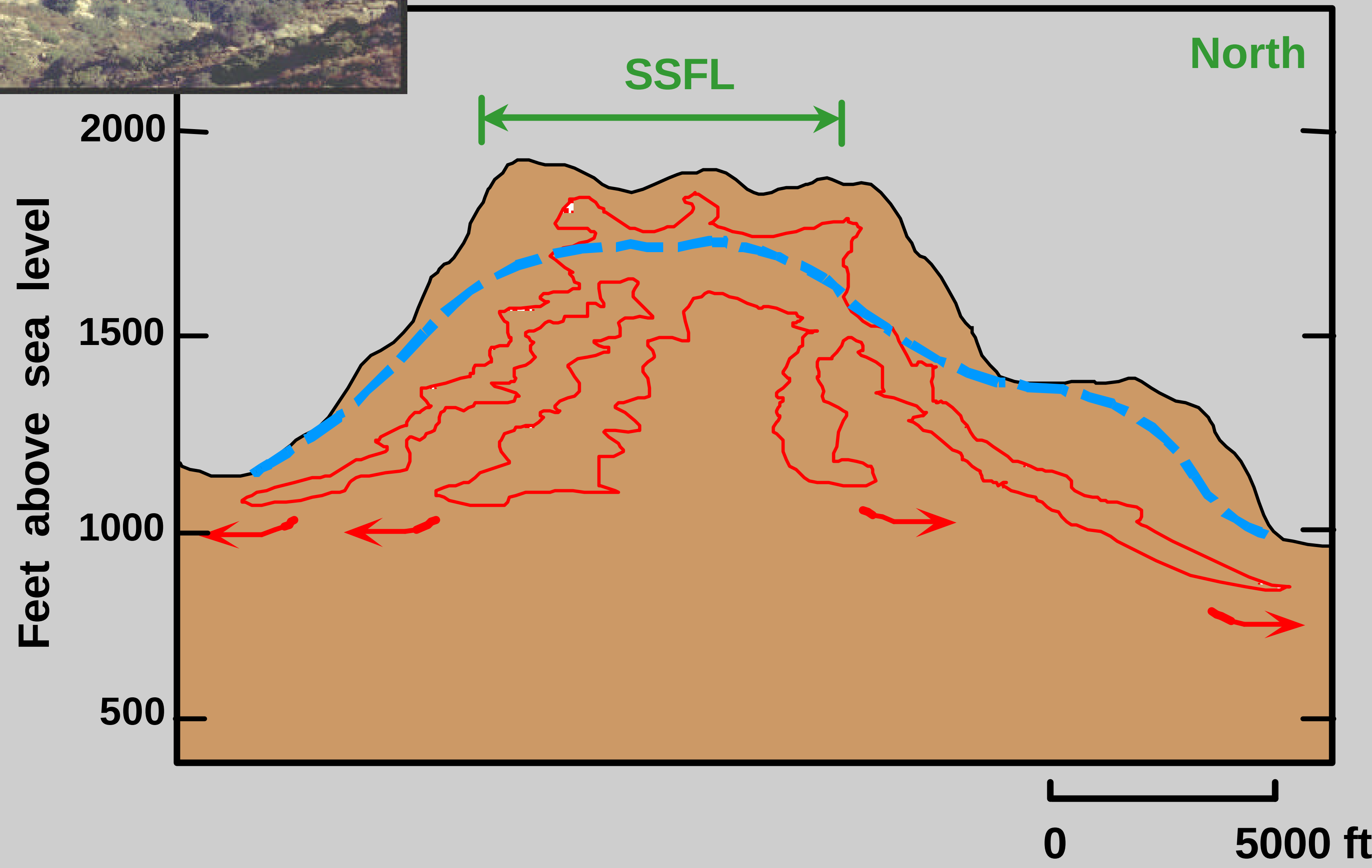
$\bar{V}$ is expected to be large even in fractured rock with low bulk hydraulic conductivity because:

$$\bar{V} = \frac{q}{\phi_f}$$

where ϕ_f is extremely small

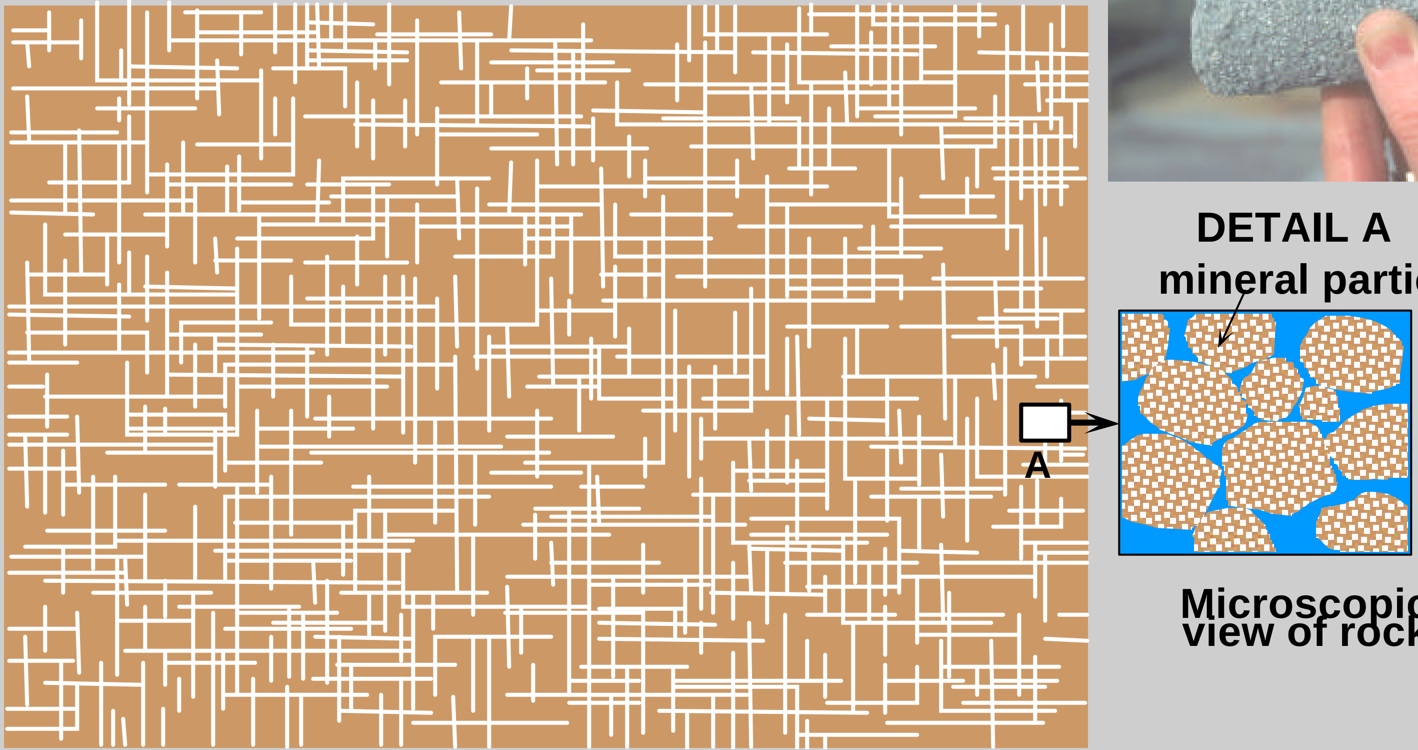
If Transport Only in Fractures, Long Plumes Occur

(Not true for SSFL)



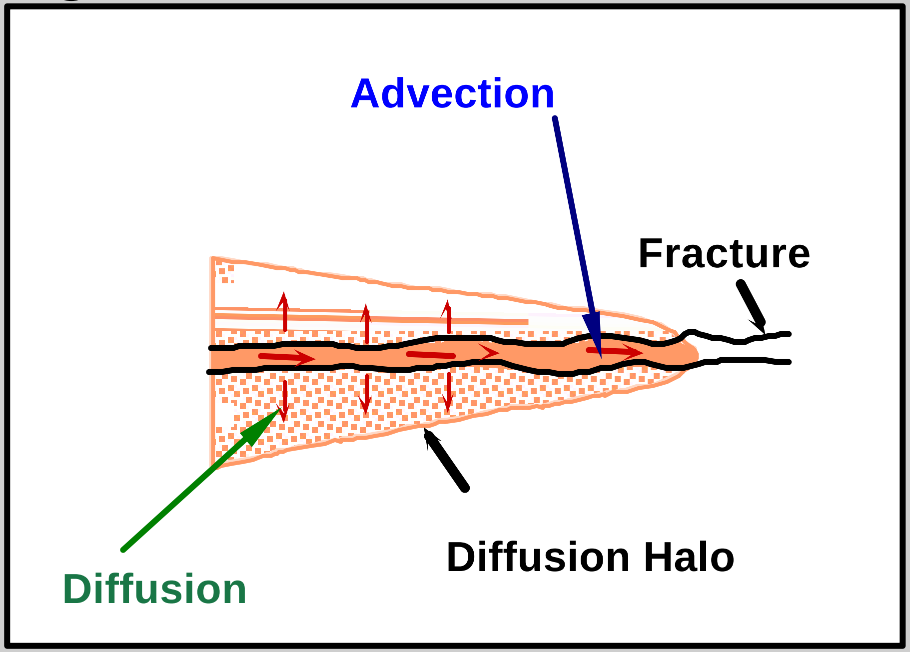
Chatsworth Formation Rock Has Large Matrix Porosity

Physical characteristics of the rock matrix allow transport and storage of chemicals from the fracture network



Two Contaminant Transport Processes

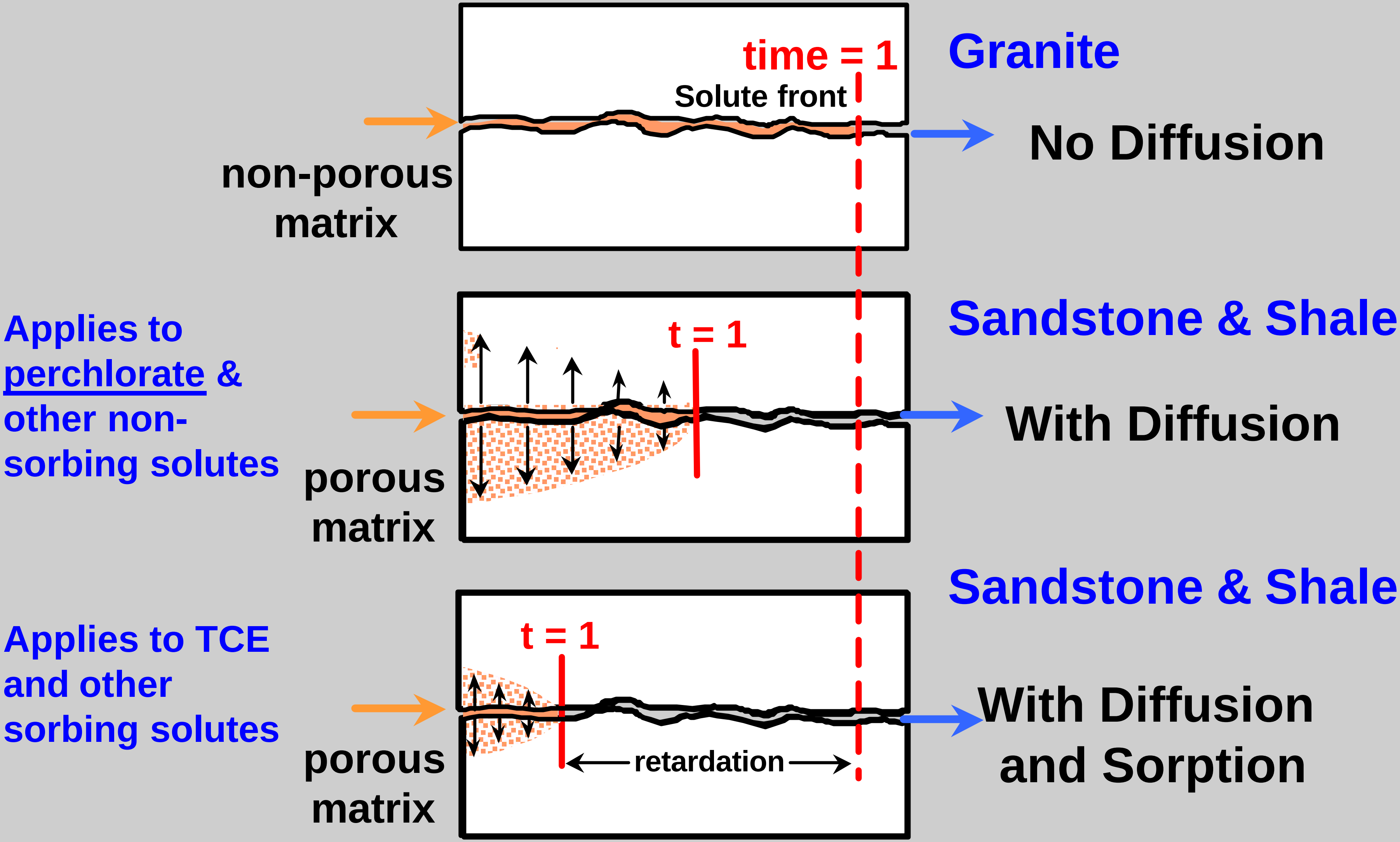
- **Advection**
  - **Bulk fluid movement (e.g., water, air)**
  - **Hydraulic gradient as driving force**
  - **Darcy's Law (1856)**



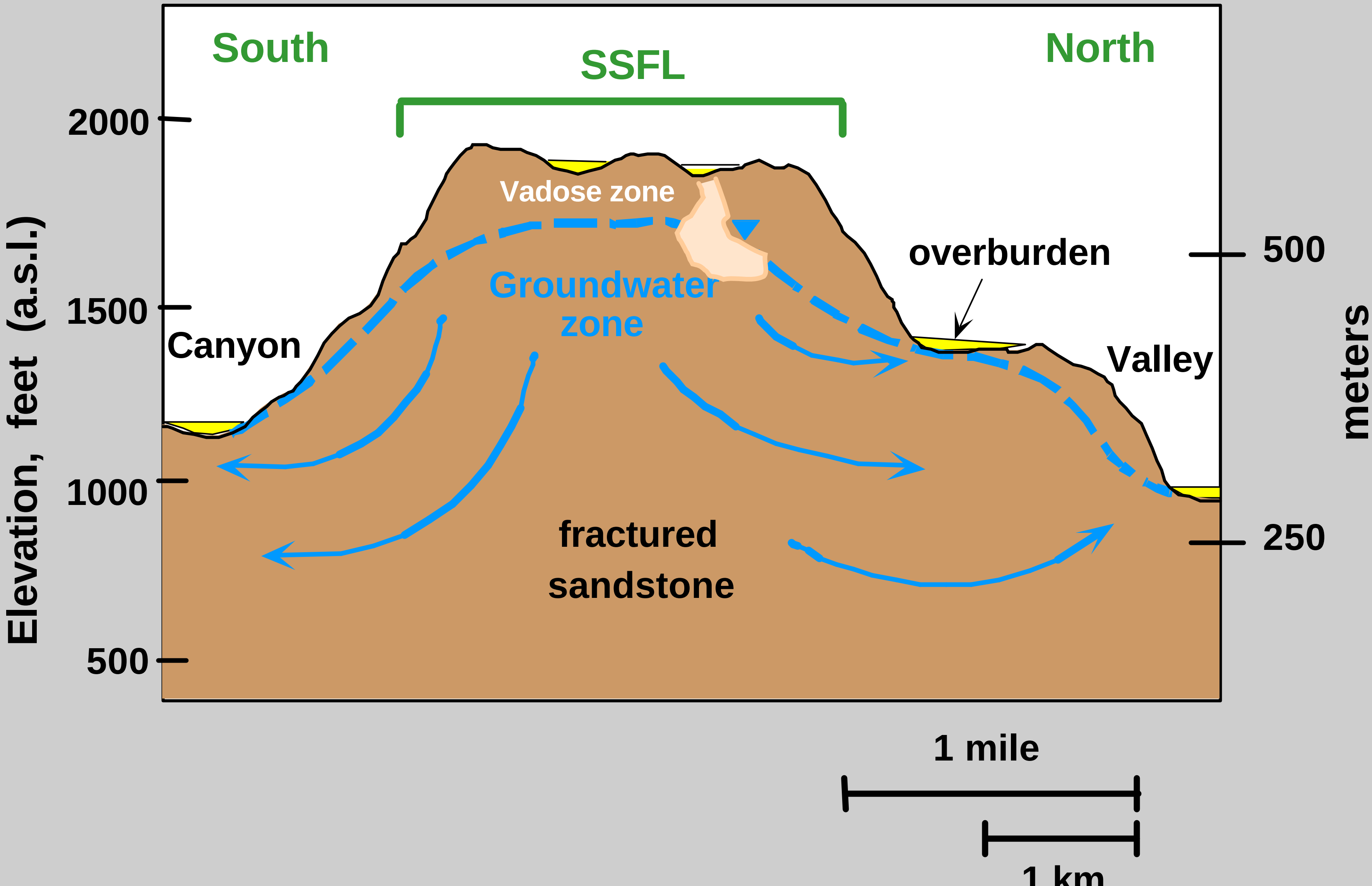
- **Diffusion**
  - **Solute movement *within* the bulk fluid**
  - **Chemical concentration gradients as driving force**
  - **Fick's Law (1852)**

Slow Transport in Sandstone is Attributed to Matrix Diffusion and Sorption

(Freeze and Cherry, 1979)



Since Contaminants are Transported in Both Fractures and Matrix *Plumes are Short* Even with High Groundwater Velocities in Fractures



What is known about the fracture number/ spacing at the SSFL?

Larger/
Fewer

Outcrop

Fracture number and spacing is a function of the type and scale of the measurement

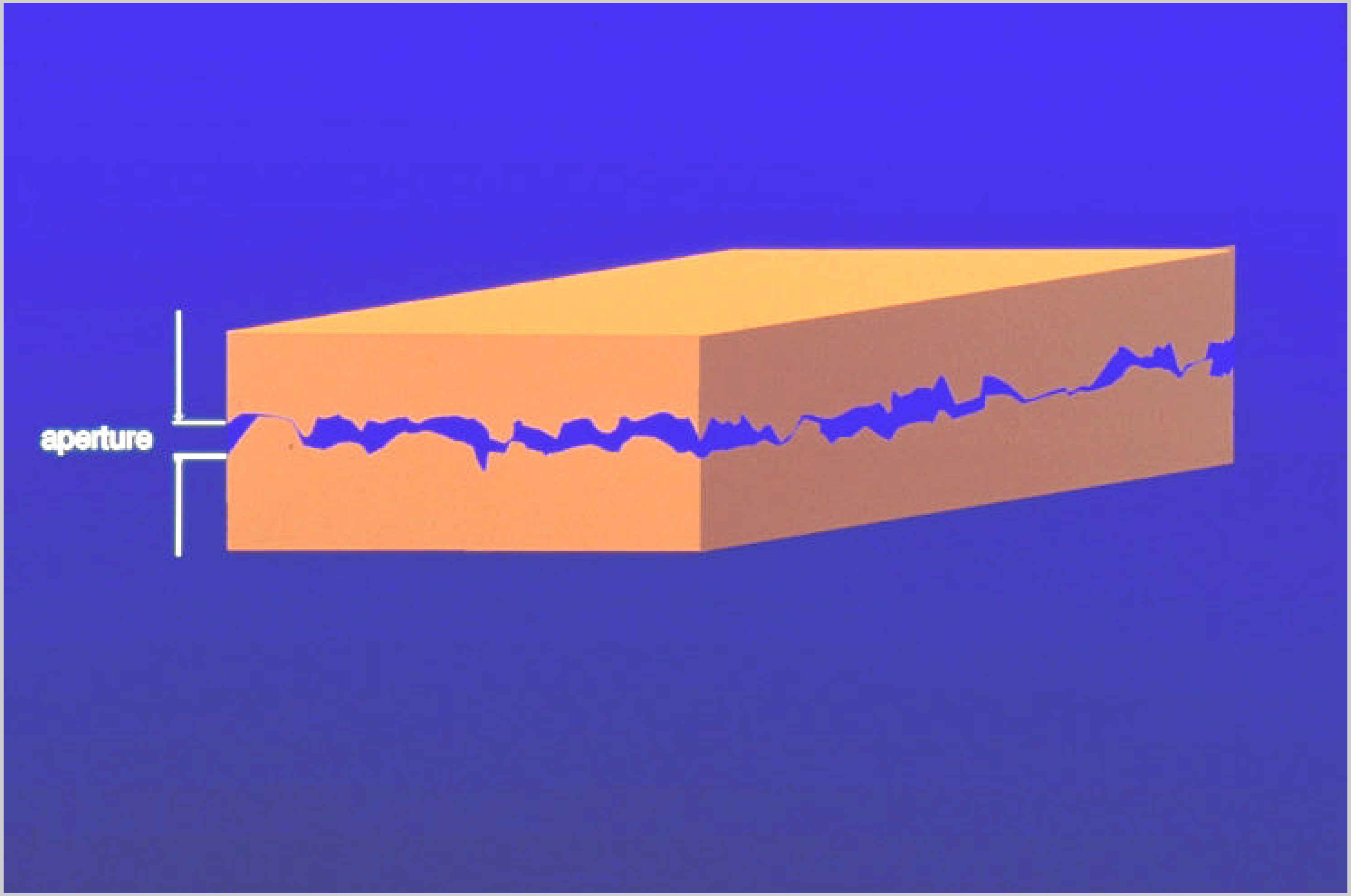
Borehole geophysics

Borehole hydraulic tests

Tracers (e.g., TCE, perchlorate)

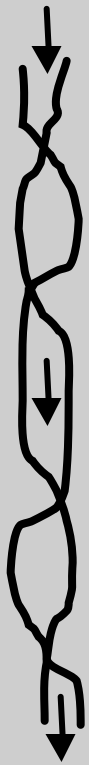
Smaller/
More

Apertures Vary Along Fracture Plane

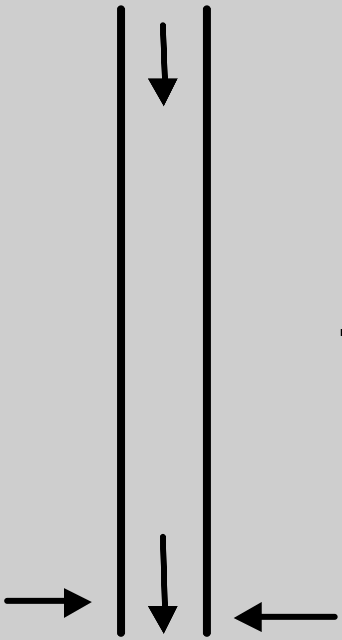


Fracture Simplification to Calculate Hydraulic Aperture

Real Fracture



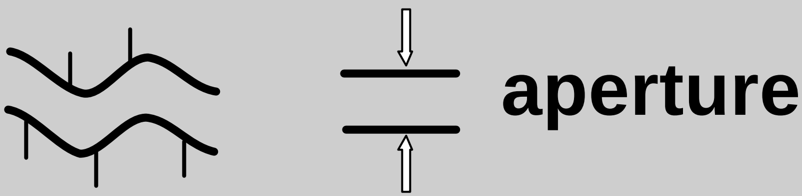
Idealized Fracture



Parallel plate fractures

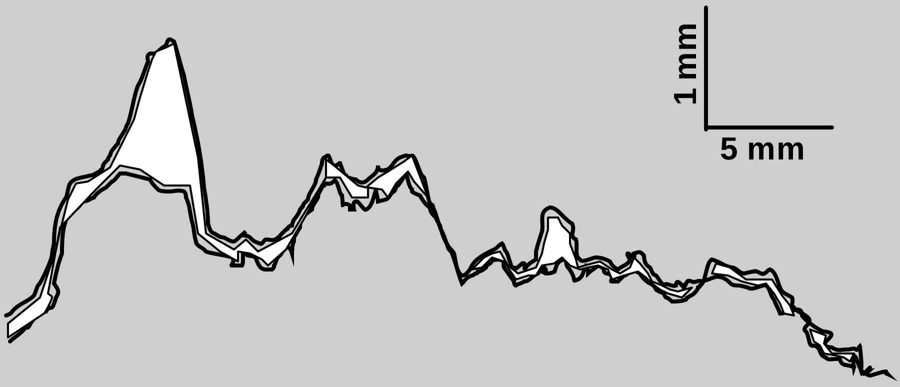
2b = aperture (microns)

Fracture Apertures are Small and Defined in Microns



- Micron (μm) ~ the unit of size
- 1000 μm = 1 millimeter
- 20 μm ~ diameter of a human hair

The apertures of real fractures vary along the fracture plane



Source: NRC, 1996

Fracture number/ spacing is a function of the type & scale of measurement

Larger/
Fewer

Smaller/
More

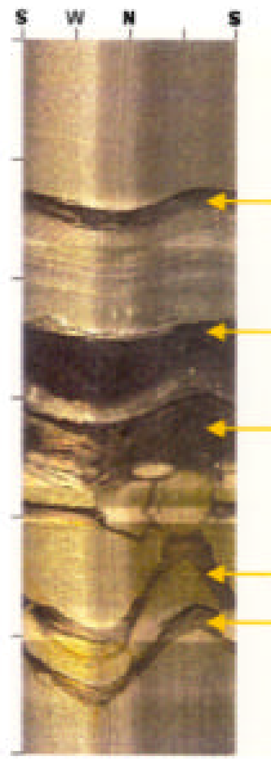
Outcrop

FRACTURES SHOWN BY BOREHOLE TELEVISION

RD-35B

ZONE 6

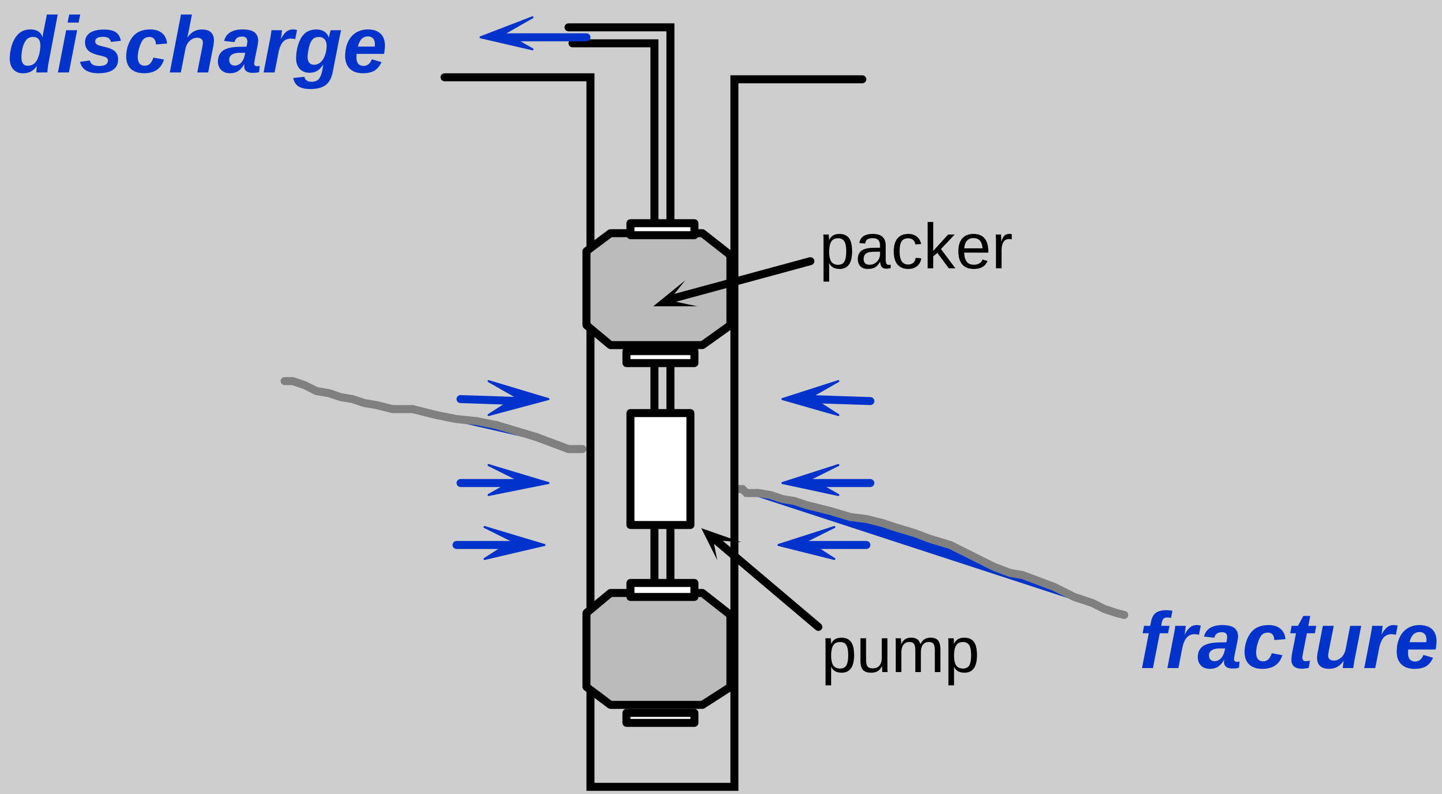
200.1 ft



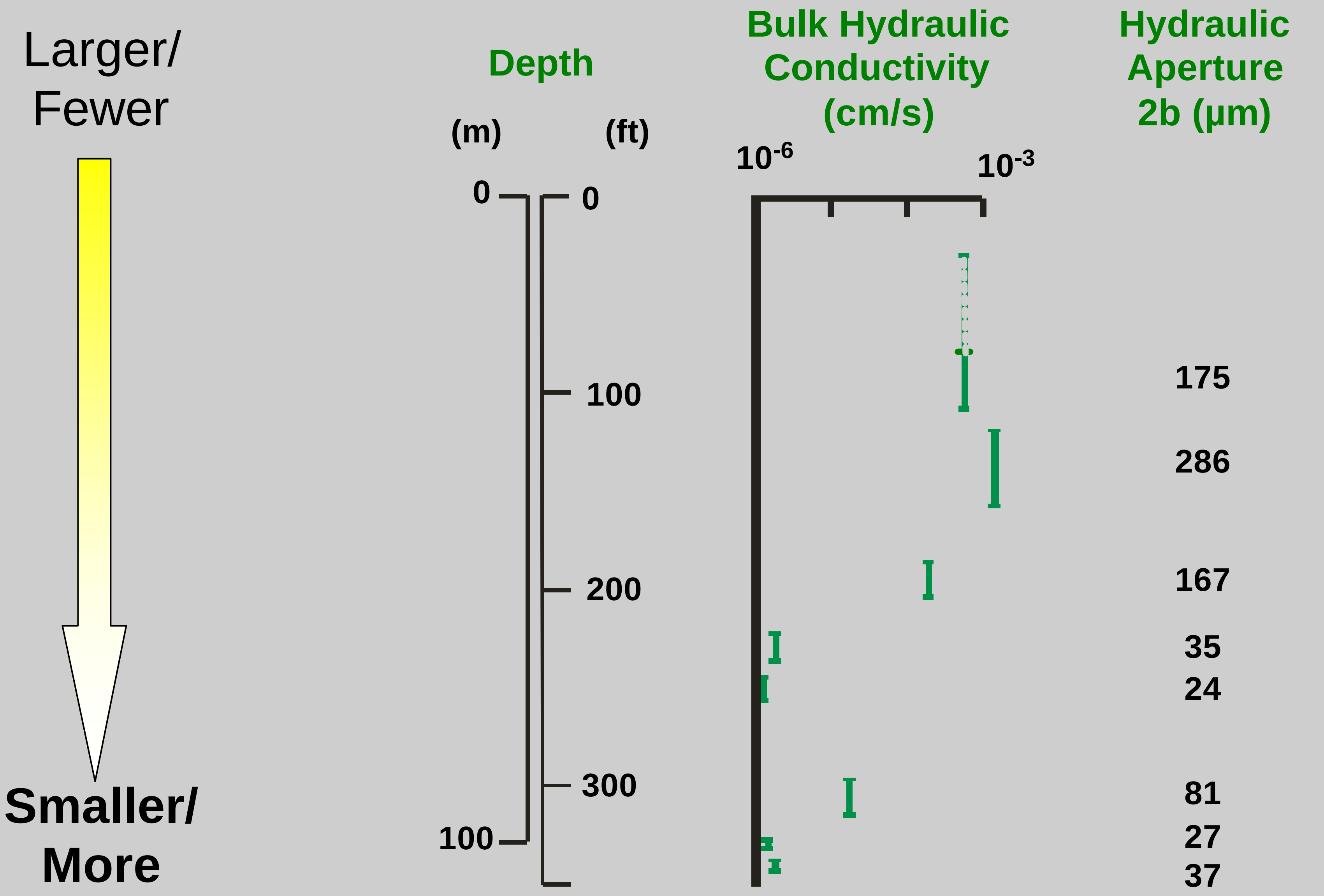
203.4

HYDRAULIC TESTING IN BOREHOLES USING DOUBLE PACKERS PROVIDE APERTURES

Borehole temporarily instrumented with packers and pump



Hydraulic Tests show Fracture Apertures to be in 10s to 100s micron range



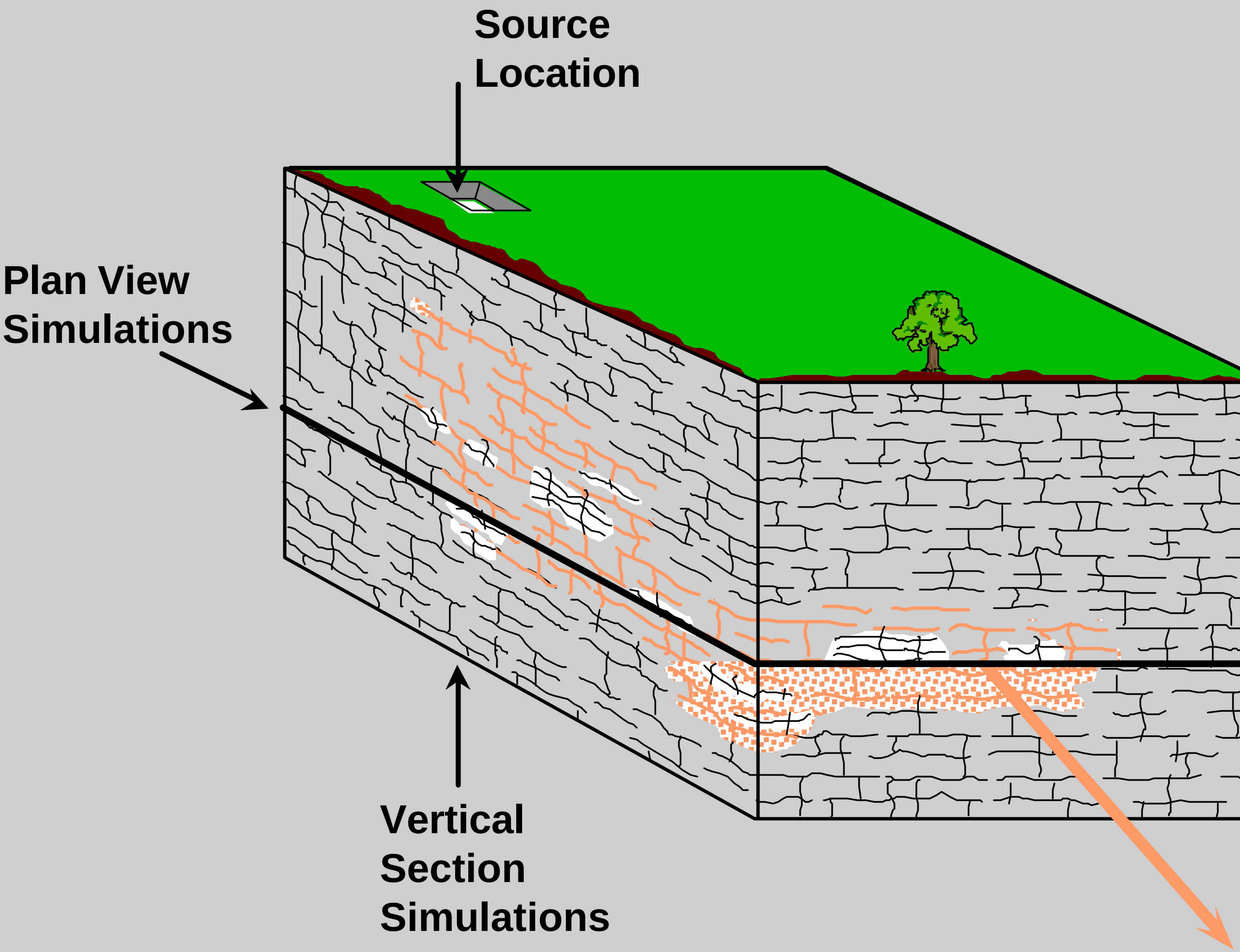
What is the nature of a perchlorate plume in fractured Chatsworth Formation sandstone?

Mathematical Models Using SSFL Parameters Help Interpret Plume Characteristics and Transport Rates & Distances

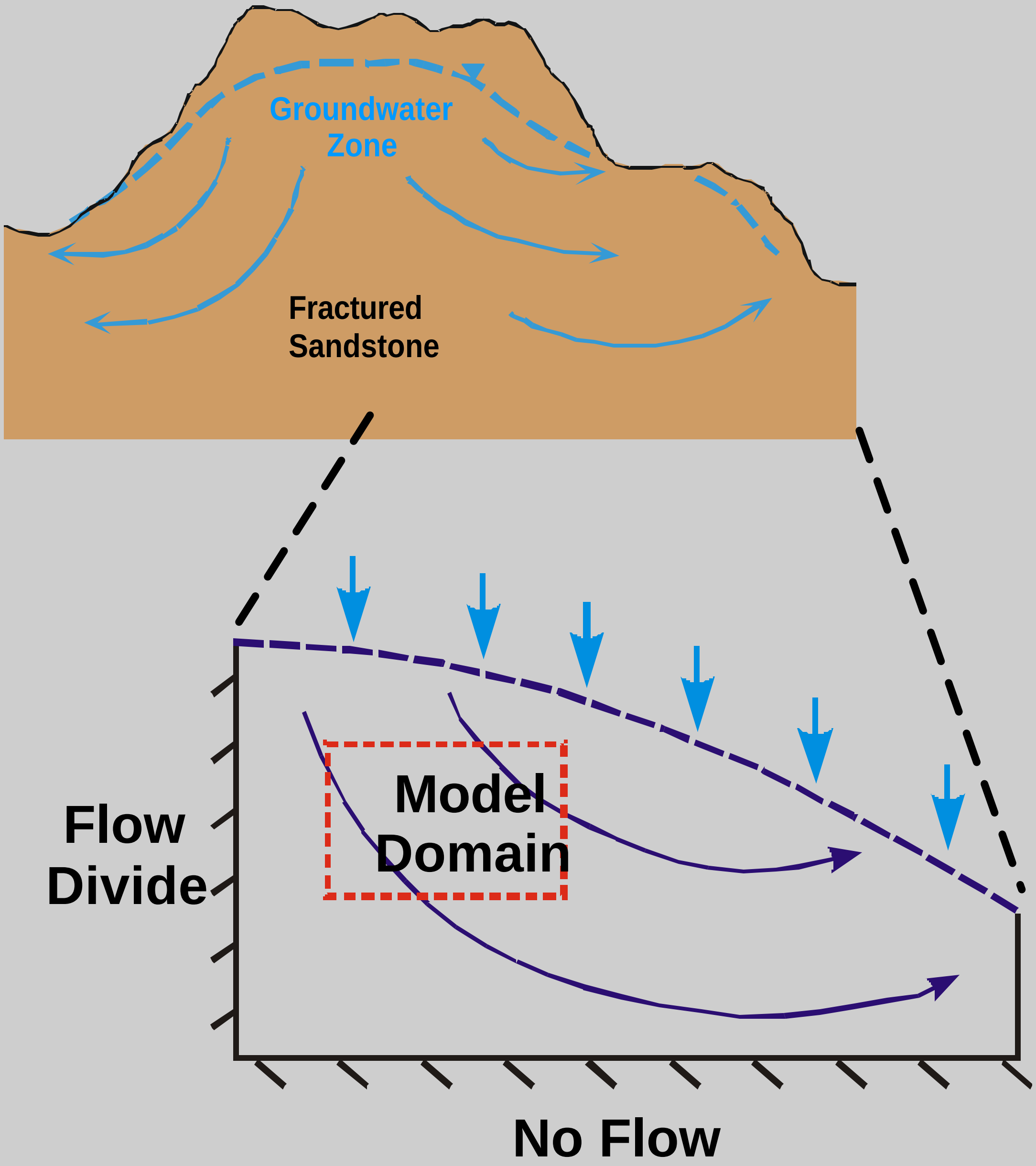
Discrete Fracture Network Modeling

- **Groundwater flow and perchlorate transport occurs in interconnected network of fractures**
- **Specifies both fracture and matrix properties to accurately quantify transport processes**
- **Design simulations and use SSFL parameters to represent the variety of site conditions**

Schematic of Plume in Fractured Sedimentary Rock

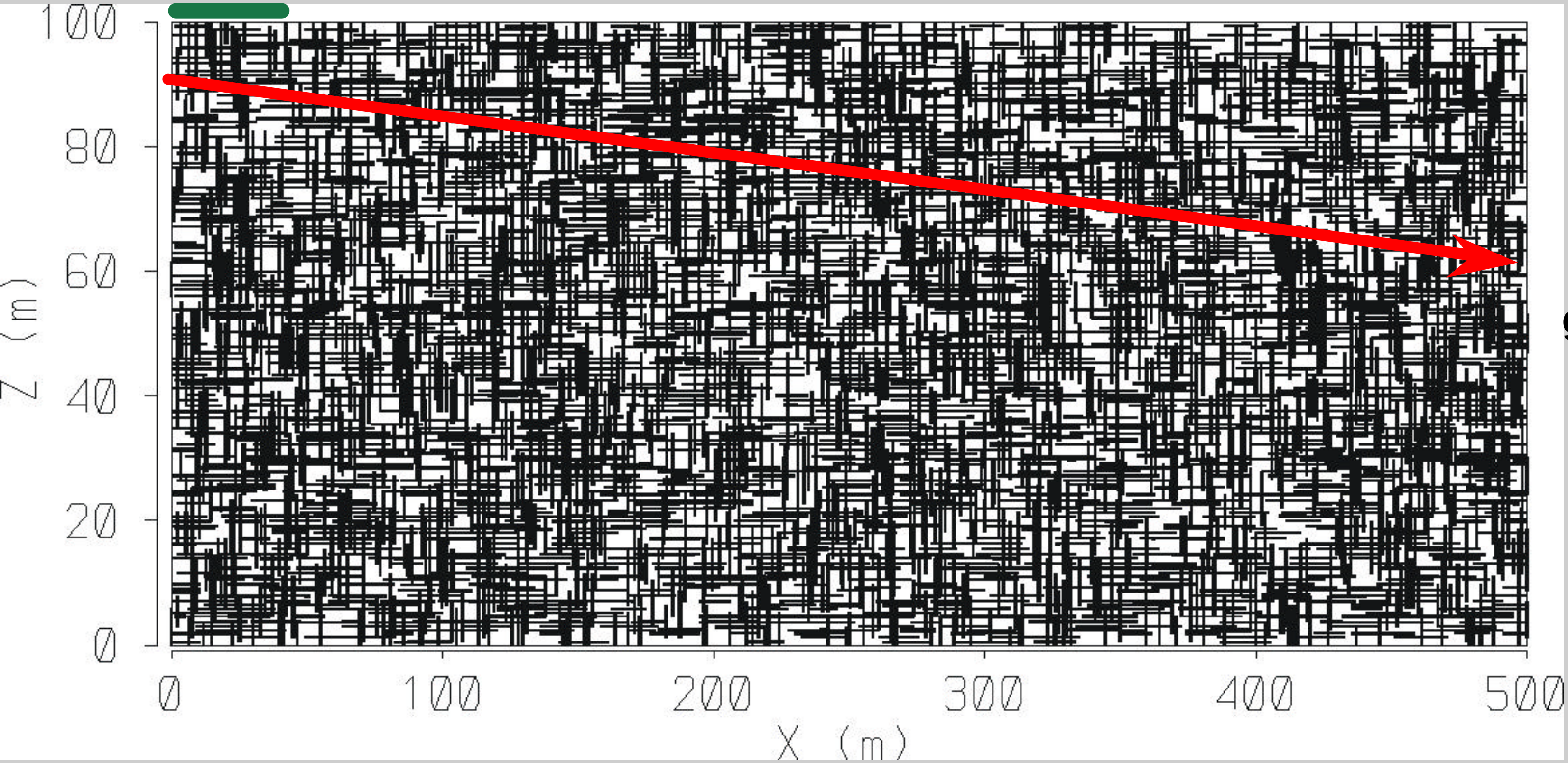


2-D Numerical Simulations in Vertical Cross-Section



Fracture network generated for transport simulations - parameters similar to measurements made at the SSFL

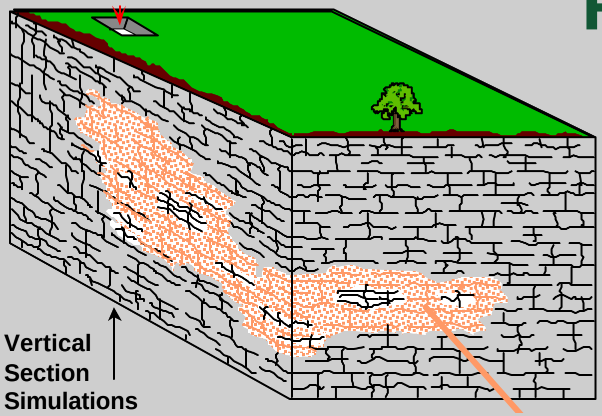
Constant perchlorate source for 10 years

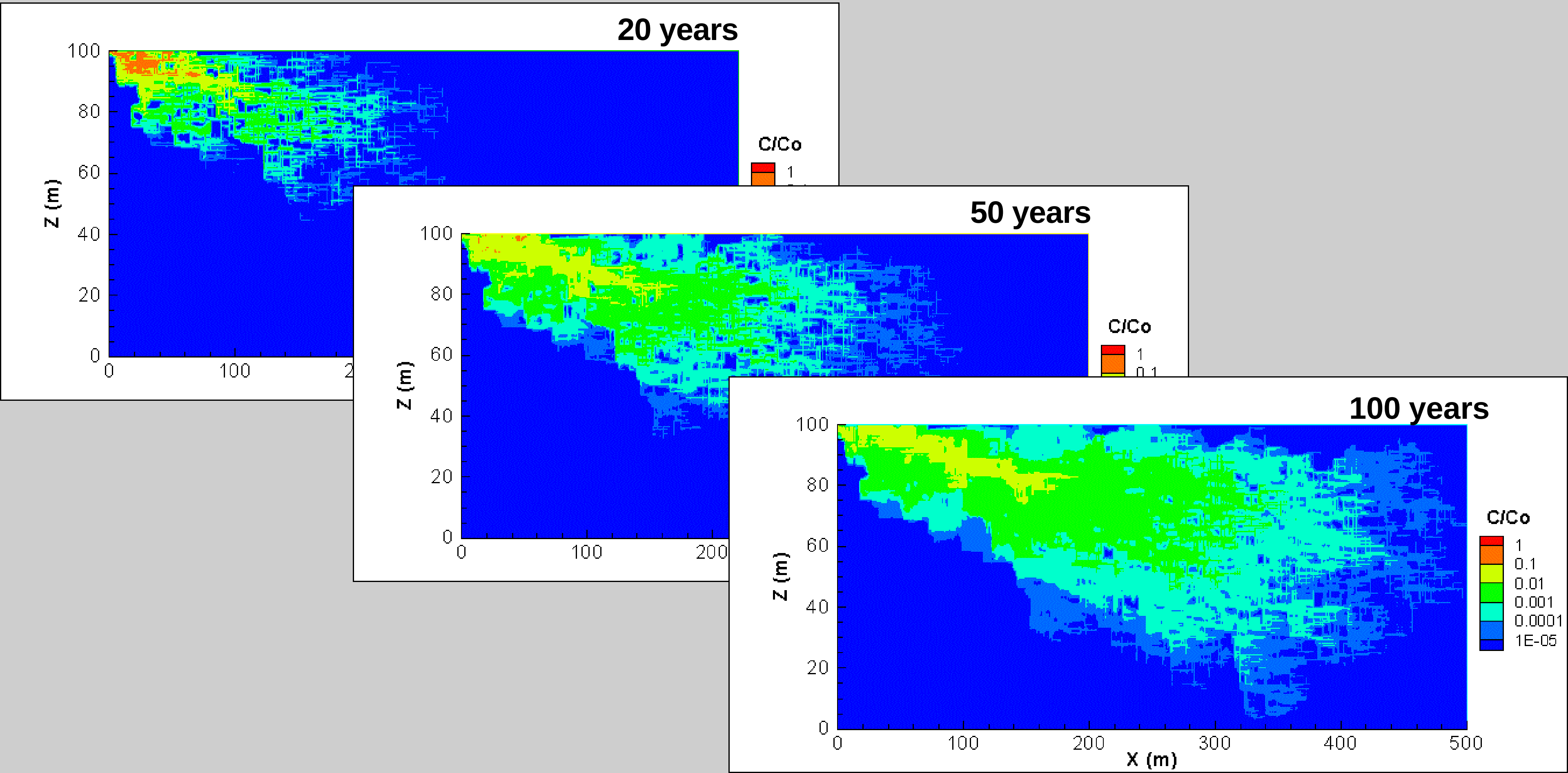


5% horizontal gradient and 2% vertical gradient

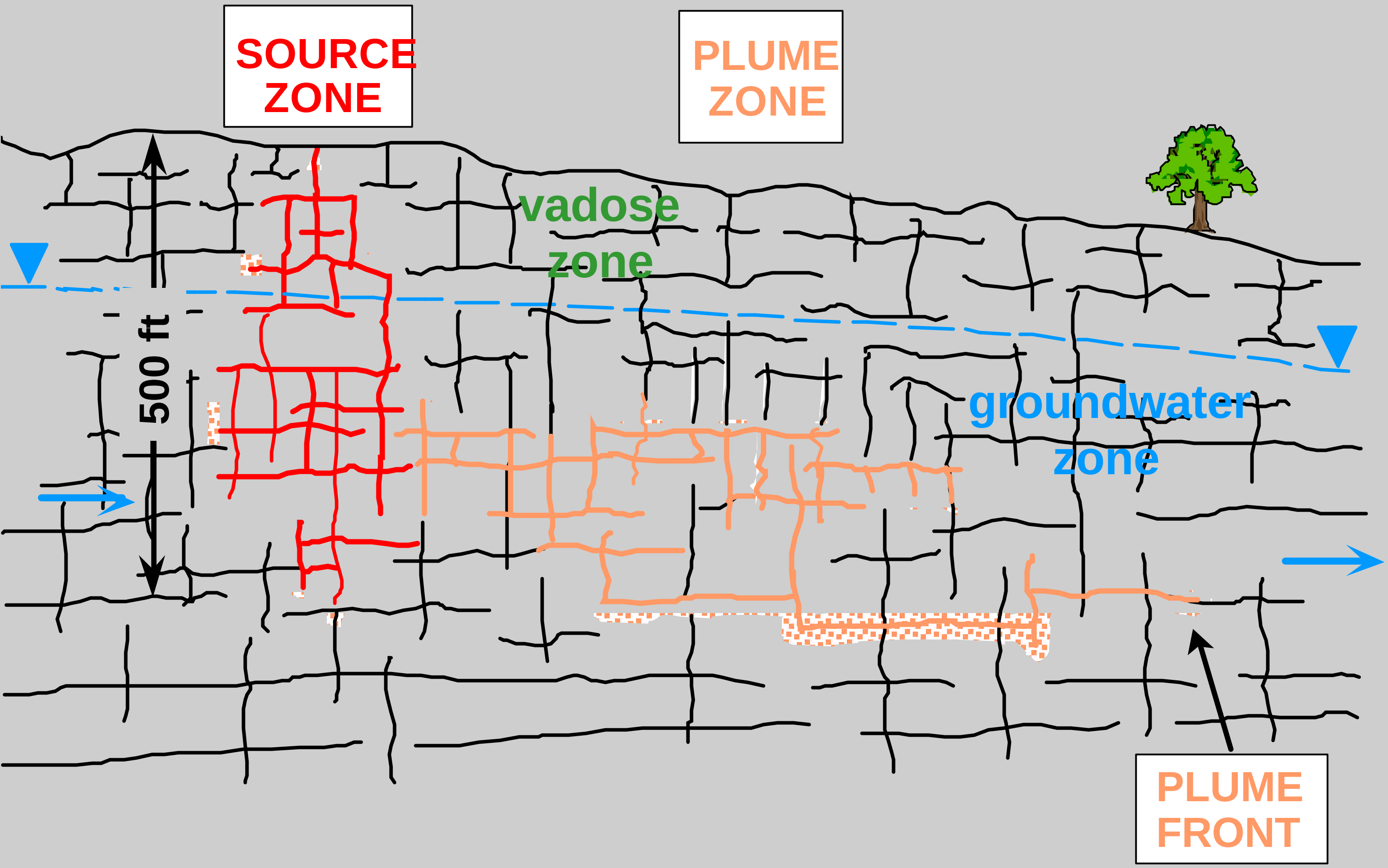
Plume at 20 to 100 yrs (Log Scale)

Base Case; Finite (10 yr) Source





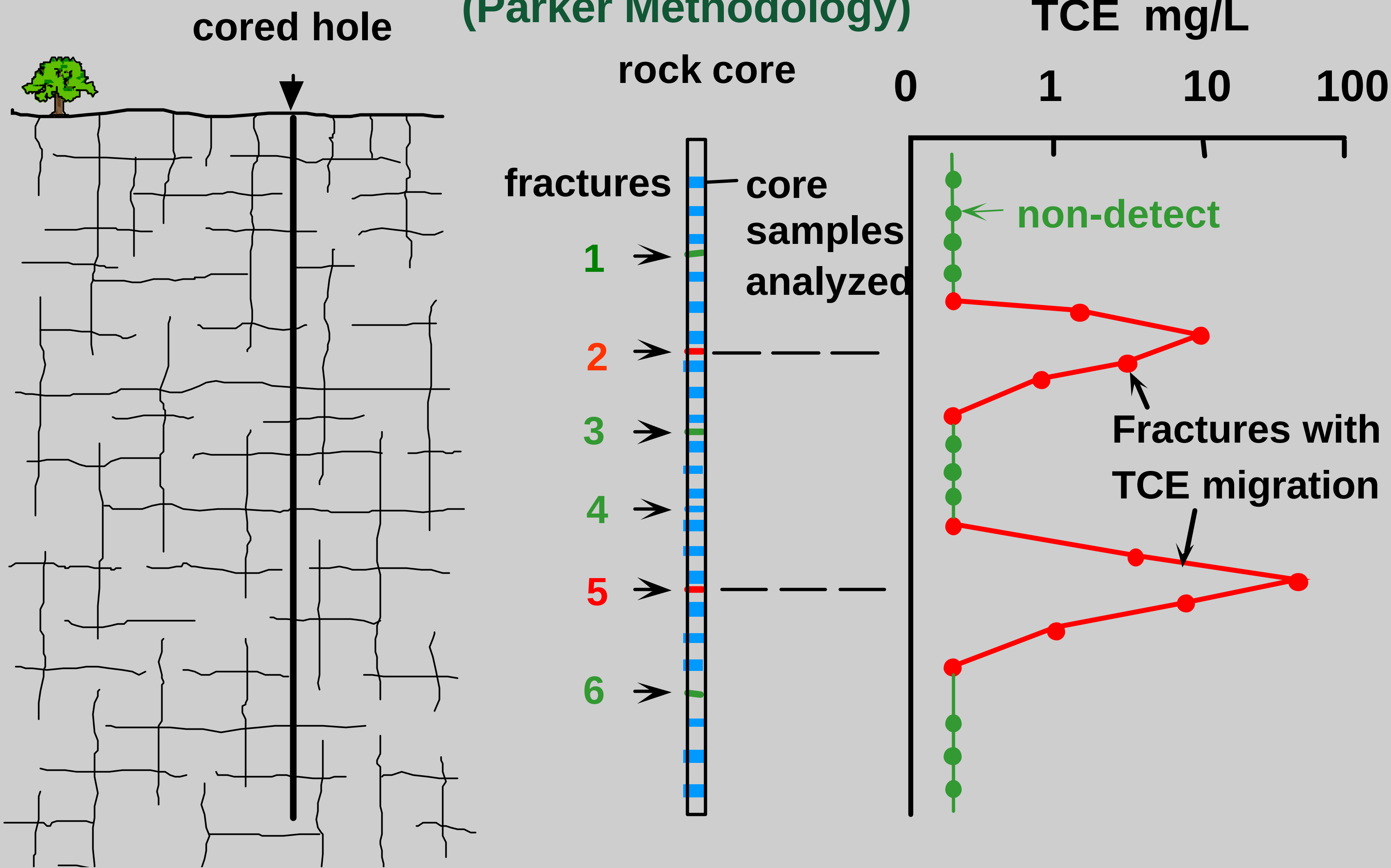
How do we know contaminants diffuse into the rock matrix?



How do we know contaminants diffuse into the rock matrix?

Core Sampling for Mass Distribution

(Parker Methodology)



Coring and Sampling Rock Matrix

Why is the transport of perchlorate at SSFL different than almost all other perchlorate sites in California?

- **The transport of perchlorate in the fractures is greatly slowed (retarded) because of molecular diffusion into the fractured rock matrix**
  - **Transport distances at the SSFL are within 1000 feet or so of release locations**

Fundamentally different than granular aquifers where there is very little diffusion

SSFL Perchlorate Summary

- Perchlorate primarily used at Bldg 359 & Happy Valley in relatively small quantities
- Extensive sampling of environmental media has been performed
- Perchlorate is found locally in soil and groundwater at these and 3 other areas (TTF, FSDF, Compound A)

SSFL Perchlorate Summary

- Sporadic detections are inconsistent with a release of perchlorate into the atmosphere

- Consistent detection in surface water at about 8 to 10 ppb in Happy Valley Drainage
  - All other drainages non-detect

- Lower permeability geologic units and faults significantly influence the groundwater flow system
  - A number of low permeability siltstones/shales and/or faults lie between the SSFL, Simi Valley and Ahmanson Ranch

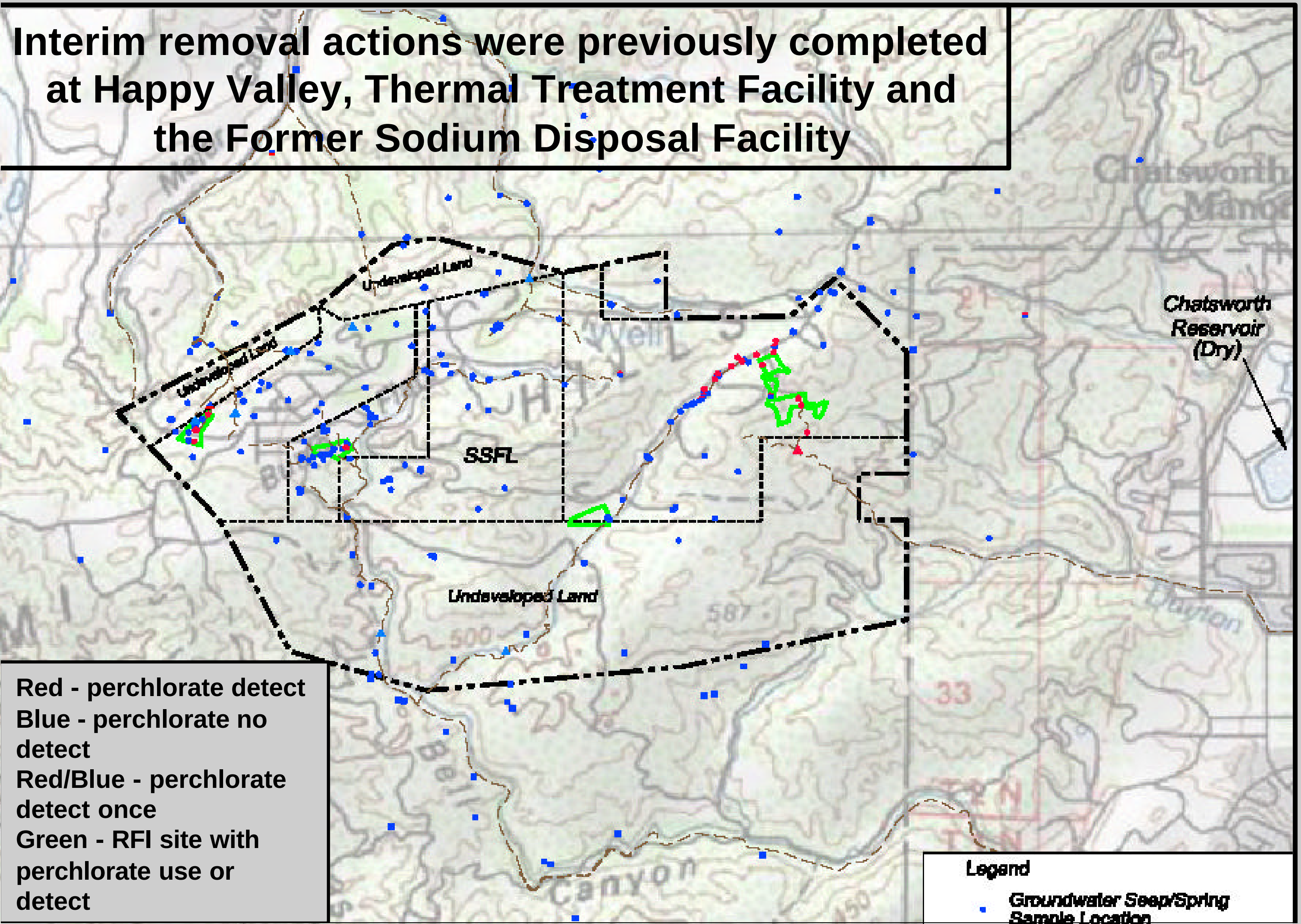
SSFL Perchlorate Summary

- **Perchlorate transport by groundwater flow in fractures is greatly slowed through molecular diffusion into the porous rock matrix**
  - **Fundamentally different than transport in granular aquifers where transport rate is ~equal to groundwater flow velocity**
  - **Transport distances at SSFL are within 1000 feet or so of release locations**

- **Data collected by SSFL, DTSC and RWQCB coupled with detailed scientific analysis show SSFL is <u>not</u> the source of perchlorate to Simi Valley or Well M-1**

Is further work necessary and if so, when will it be completed?

Interim removal actions were previously completed at Happy Valley, Thermal Treatment Facility and the Former Sodium Disposal Facility

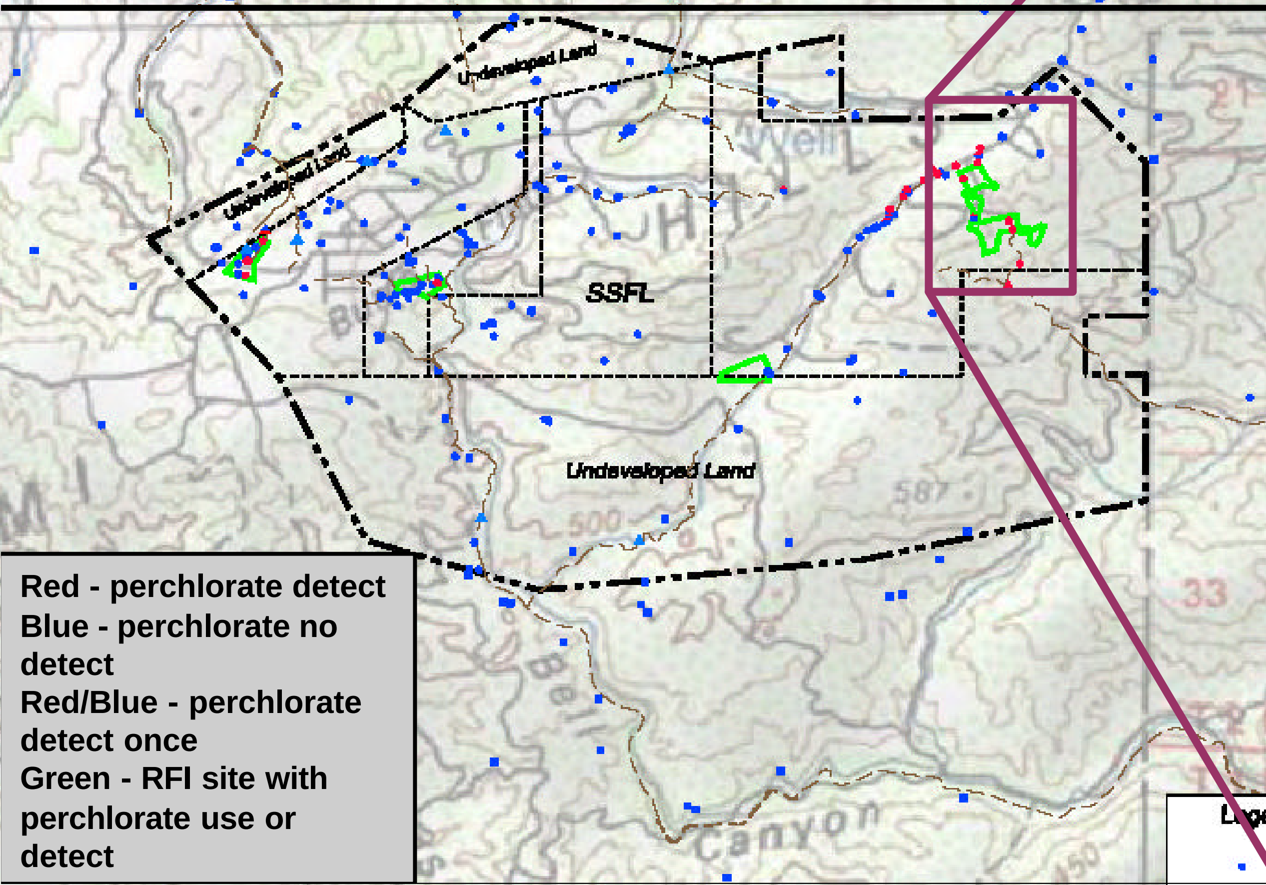


Red - perchlorate detect
Blue - perchlorate no detect
Red/Blue - perchlorate detect once
Green - RFI site with perchlorate use or detect

Is further work necessary and if so, when will it be completed?

Source removal actions are being planned at both Building 359 and Happy Valley during the summer

Other longer-term actions to be taken after completing corrective measures study



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